Rubble Stone Masonry Buildings with Cement Mortar: A Comparative Review of Seismic Design Specifications, Cost Implications and Base Shear Seismic Demand on a Worldwide Scale

セメントモルタルを用いた不整形石積組積造建物：耐震設計規準・耐震化コスト・要求耐震性能の国際的比較検討

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真実の愛を君だけにとう

Rubble Stone Masonry Buildings with Cement Mortar:
A Comparative Review of Seismic Design Specifications, Cost Implications and Base Shear Seismic Demand on a Worldwide Scale

by
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Abstract

This thesis questions the current state-of-the-art and knowledge levels regarding the seismic behavior and resilience of "non-engineered" vernacular construction techniques, and in particular rubble stone masonry buildings. The term "non-engineered" in construction refers to buildings as "those which are spontaneously and informally constructed in various countries in the traditional manner, without any or little intervention by qualified architects and engineers in their design". Such techniques rarely behave well in earthquakes, and the most devastating levels of damage and loss occur in developing countries, such as in the recent disasters in Kashmir (2005), Haiti (2010) and Nepal (2015). Fact is that an estimated number of 217 million people will continue to live in stone houses in the Himalayan region alone, and likely in regions in Central Asia, the Middle East and Northern Africa as well, affecting the lives of several hundreds of millions of people globally.

In-depth reviews of the seismic features of "non-engineered" and vernacular techniques show that the national codes, technical regulations and practical manuals are outdated, contain many contradictions, and have become ambiguous. This raises questions about the completeness and correctness, as well as about the reliability and actual value of the knowledge in this field. A first important step is the acknowledgment of the current situation, for which the following statement with a call to action is prepared:

i) High-tech seismic design of concrete and steel structures is based on peer-reviewed scientific research and validated engineering practice. This has resulted in national and international building codes that govern the seismic resilience of such structures and which form the basis for government agencies and the construction industry.

ii) Low-tech seismic design of vernacular buildings is not based on peer-reviewed scientific research and validated engineering knowledge. It mostly relies on rules of thumb and best practice. Standards and guidelines for such structures are often outdated, contradictory and incomplete, and in the main are not fit for purpose.

iii) To properly address low-tech seismic design and construction of vernacular buildings, we must first acknowledge these shortcomings.

iv) The acknowledgment must be accompanied by the prioritization of scientific research, focused on advancing our understanding and improving the resilience of low-tech vernacular buildings in seismic events.

v) This call to action will focus on producing national and international building codes for low-tech vernacular buildings in seismic areas. These will be based on validated scientific research by means of the current state-of-the-art for calculating, testing and modeling. This work will be translated into simplified and practical seismic construction guidelines for local practitioners.

To address the shortcomings, a research initiative is started by the name of SMARTnet, which stands for **S**eismic **M**ethodologies for **A**pplied **R**esearch and **T**esting of **n**on-**e**ngineered **t**echniques. The strategy of SMARTnet envisions a joint and multi-disciplinary approach of global collaboration, to fully assess, validate, optimize and complement the existing knowledge of non-engineered techniques, by means of the current state-of-the-art for calculating, testing and modeling. A further aim is to cope with the massive number of material variables and to generate cross-checked data that can be used for calculations and computer modeling of non-engineered techniques. The time has come for "Non-Engineered 2.0".

This thesis is the starting point and addition toward the overall objectives of SMARTnet and covers various aspects of the seismic demand determination of a specific vernacular construction type. The primary research objective of the thesis is: "What is the state-of-the-art of practical seismic applications and seismic code provisions for nominally reinforced rubble stone masonry buildings with cement mortar?" The core of this thesis is divided into three main parts.

The first part is a global review of the state-of-the-art regarding the knowledge levels of rubble stone masonry buildings in seismic areas, to determine where we stand today and how the knowledge is perceived. A total of 47 practical field manuals and 325 national seismic and masonry codes have been analyzed and compared. No consensus was found on any of the design specifications and main dimensions between these countries and the differences vary greatly.

The second part analyzes detailed and localized cost comparisons of the earthquake-resistant elements in masonry structures, based on unique local costing data in Nepal, spanning a period of ten years.

The third part works toward the development of practical applications and structural solutions. It includes base shear seismic demand calculations which are performed on two case study buildings, according to the seismic codes of nine selected countries. The base shear and story shears are calculated for a design PGA of 0.20g, as well as the effects of critical load combinations on the Axial Forces (N), Shear Forces (V) and Bending Moments (M), that are acting on the lateral-resisting elements. These findings will be used as the reference for the upcoming refinements of the calculation models and their seismic capacity verifications, to be published in future papers.

It is realized that the overall challenge and amount of work is enormous, and help is required. Therefore, the thesis concludes with an international call for collaboration with the SMARTnet projects. SMARTnet invites experts, professionals, academics and final-year students to exchange their knowledge and to support the projects with their time and expertise.

Acknowledgments

I would like to express my sincerest gratitude to everyone who has supported and assisted me during my research and studies. Throughout the years you have shown patience and dealt with my outspoken views and many questions. My progress in this specific field of research, as well as my personal development as a researcher, would not have been possible without your ongoing support, and I cannot thank you all enough.

I want to thank my supervisors, first and foremost Professor Yoshikazu Araki for allowing me to start a new career as a researcher in Japan, as well as Professor Stefano Silvestri for hosting me during my stay in Italy. I largely based this thesis on 10 years of on-site work experience in developing countries as an architect, designer and builder. The biggest challenge for me was to become a student again, embarking on a journey to learn the basics of earthquake engineering, material mechanics and the seismic behavior of masonry structures. I am grateful for their invaluable guidance, advice, dedication, patience, encouragements, lectures and discussions. More important, I regard them both as dear friends.

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A massive hug to family and friends who support me no matter what, and most important of all, to the real rock in my life (even though she can't hear the word stone anymore)…

List of Published Writings

Many passages, figures and tables in this thesis are reproduced verbatim from the following papers and proceedings that are written by Martijn Schildkamp as the primary author. These are peer-reviewed and published at Frontiers in Built Environment, in the Section Earthquake Engineering, under the Research Topic "Seismic Risk Reduction in Developing Countries".

Frontiers is an open-source journal, meaning that the papers can be downloaded for free by everyone through the links provided. As of May 2021, the first 3 papers in this series have a combined number of views and downloads of 22,500+, of which the first paper is ranked in the top 8%, meaning it has more views and downloads than 92% of all Frontiers articles (219,000+ in total).

The last paper in this list is published as proceedings of the 17th World Conference on Earthquake Engineering in Sendai, Japan. Although all topics are related and connected, it is aimed to present the chapters as stand-alone sections that can be read separately. As a result, some minor repetition of passages may occur.

1. Schildkamp, M., and Araki, Y. (2019a). School Buildings in Rubble Stone Masonry with Cement Mortar in Seismic Areas: Literature Review of Seismic Codes, Technical Norms and Practical Manuals. Front. Built Environ. 5:13. doi: 10.3389/fbuil.2019.00013
www.frontiersin.org/articles/10.3389/fbuil.2019.00013/full

2. Schildkamp, M., and Araki, Y. (2019b). Cost Analysis of Mountain Schools in Nepal: Comparison of Earthquake Resistant Features in Rubble Stone Masonry vs. Concrete Block Masonry. Front. Built Environ. 5:55. doi: 10.3389/fbuil.2019.00055
www.frontiersin.org/articles/10.3389/fbuil.2019.00055/full

3. Schildkamp, M., Araki, Y. and Silvestri, S. (2020). Rubble Stone Masonry Buildings with Cement Mortar: Design Specifications in Seismic and Masonry Codes Worldwide. Front. Built Environ. 6:590520. doi: 10.3389/fbuil.2020.590520
www.frontiersin.org/articles/10.3389/fbuil.2020.590520/full

4. Schildkamp, M., Araki, Y. and Silvestri, S. (2021). Rubble Stone Masonry Buildings with Cement Mortar: Base Shear Seismic Demand Comparison for Selected Countries Worldwide. Front. Built Environ. 7:647815. doi: 10.3389/fbuil.2021.647815
www.frontiersin.org/articles/10.3389/fbuil.2021.647815/full

5. Schildkamp, M., Araki, Y. and Silvestri, S. (2020). "Non-Engineered 2.0 – Renewed Philosophies for Improving the Seismic Performance of Non-Engineered Construction" in Proceedings of the 17th World Conference on Earthquake Engineering (Sendai).

Further Contributions

Further contributions have been made to the following books and papers as published by other authors, as well as the publication of technical manuals by Martijn Schildkamp:

6. Schildkamp, M. (2009). Suitability of Local Soil for Cost-Saving Construction Techniques, with Soil Tests in Nepal. Published under Smart Shelter Foundation.

7. Bothara, J., and Brzev, S. (2011). A tutorial: Improving the Seismic Performance of Stone Masonry Buildings, 1st Edn. Oakland: Earthquake Engineering Research Institute (EERI).

8. Schildkamp, M. (2015a). Rules of Thumb for Building Safe Non-Engineered Buildings with Random Rubble Stone Masonry. Published under Smart Shelter Research.

9. Schildkamp, M. (2015b). Rules of Thumb for Building Safe Non-Engineered Buildings with Hollow Concrete Block Masonry. Published under Smart Shelter Research.

10. Schildkamp, M. (2015c). Rules of Thumb for Building Safe Non-Engineered Buildings - Choosing the Right Materials and Quality Control. Published under Smart Shelter Research.

11. Laghi, V., Palermo, M., Trombetti, T. and Schildkamp, M. (2017) Seismic-Proof Buildings in Developing Countries. Front. Built Environ. 3:49. doi: 10.3389/fbuil.2017.00049

12. Carabbio, R., Pieraccini, L., Silvestri, S., and Schildkamp, M. (2018). How Can Vernacular Construction Techniques Sustain Earthquakes: The Case of the Bhatar Buildings. Front. Built Environ 4:18. doi: 10.3389/fbuil.2018.00018

Conflict of Interest Statement

I declare that the above-mentioned research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

List of Figures

List of Tables

Abbreviations and Acronyms

$10\%PE_{50y}$	10% Probability of Exceedance within 50 years of Service Life
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BoQ	Bill of Quantity
CM	Confined Masonry
DR	District Rates (of Nepal)
DPC	Damp Proof Course
EC	Eurocode
EERI	Earthquake Engineering Research Institute
ELF	Equivalent Lateral Force (method)
EN	European Norm
GB	Guobiao Standard (Chinese National Standard)
GOST	Gosudarstvennyy Standart (Russian Governmental Standard)
HSD	High-Strength Deformed (steel bars)
IAEE	International Association for Earthquake Engineering
IS	Indian Standard
MCE	Maximum Considered Earthquake
MSK	Medvedev-Sponheuer-Karnik (Intensity Scale)
NICEE	National Information Centre of Earthquake Engineering
NBC	National Building Code (of Nepal)
NGO	Non-Governmental Organization
NRA	National Reconstruction Authority (of Nepal)
NRM	Nominally Reinforced Masonry
NRS	Nepalese Rupee

PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Analysis
RM	Reinforced Masonry
RP_{475}	475-year Return Period
SDC	Seismic Design Category
S-ELF	Simplified Equivalent Lateral Force (method)
S-Modal	Simplified Modal (response spectrum method)
SLS	Serviceability Limit State
SMARTnet	Seismic Methodologies for Applied Research and Testing of non-engineered techniques
SNiP	Stroitelnye Normy i Pravila (Russian Construction Codes and Regulations)
SSF	Smart Shelter Foundation
UBC	Uniform Building Code
ULS	Ultimate Limit State
URM	Unreinforced Masonry
U$	United States Dollar

Table of Contents

Chapter 1

Introduction

Summary

How can we accurately predict and significantly strengthen the seismic performance of so-called "non-engineered" vernacular and traditional techniques, yet with basic engineering principles? How can we improve the quality of local construction practices with simple skills, and effectively implement national standards in affordable ways? These key questions have not been adequately addressed to date. Vernacular building types include numerous variables that are highly dependent on site-specific parameters for local construction quality, materials and workmanship. From an engineering perspective, these variables are not fully integrated in current calculations and models, and a methodology that includes such parameters is currently non-existent.

To address any shortcomings, renewed philosophies and technological strategies are necessary; the time has come for "Non-Engineered 2.0". This thesis is the starting point and catalysator of that journey, in which several recommendations and solutions are proposed under the name SMARTnet, which stands for "**S**eismic **M**ethodologies for **A**pplied **R**esearch and **T**esting of **n**on-**e**ngineered **t**echniques".

1.1 Background and Context

1.1.1 Motivation of the Research

Between 2007 and 2012, the Dutch non-for-profit organization Smart Shelter Foundation (SSF) built several earthquake-resistant schools in rubble stone masonry and cement block masonry in Nepal. The designs were made by Martijn Schildkamp, architect and author of this thesis, by using the design rules that were obtained from numerous technical guidelines and practical manuals that can be found online. These general rules of thumb are commonly referred to as "best practice" or "non-engineered construction principles". Professor A.S. Arya from India, one of the research pioneers on the seismic behavior of such techniques, defines non-engineered buildings as "those which are spontaneously and informally constructed in various countries in the traditional manner, without any or little intervention by qualified architects and engineers in their design" (Arya, 2000).

While studying the existing documentation and preparing the school building designs with the available information, it was the personal experience of Schildkamp that this information was often unclear, contradictory and incomplete. During the construction of the projects, many technical questions and practical issues came to light that were not properly addressed in the literature. He consulted several members of the Earthquake Engineering Research Institute (EERI), regarding basic requirements for plan dimensions, horizontal bands and vertical reinforcements. The questions were reviewed and discussed by a group of EERI members until a consensus was reached and a collective personalized recommendation was formulated, which was followed and executed by Smart Shelter Foundation. However, during the discussions it became apparent that the received information relied heavily on opinions and assumptions, but it was not based on scientific proof.

One such question is whether vertical steel rods must be inserted in the corners, t-sections and next to openings of the rubble stone masonry walls. Over the years, this question has been asked to several hundreds of experts globally, and the answers are divided almost evenly between yes and no. The consensus of the EERI group was that it is not recommended, for which several reasons were given. First, the buildings are very heavy, and during a seismic event, large lateral forces will be generated. It is questionable that single steel rods will provide enough ductility and energy dissipation that justifies their presence. Second, it is reasoned that including vertical elements at critical junctions is making the connections weaker, rather than stronger. And third, to insert these vertical elements in the walls and then protect them by casting concrete cores or concrete posts around them for protection, is difficult to achieve at the worksite. These thin concrete elements are usually cast in lifts of 60cm, resulting in elements that are not homogenous and of weak quality. For all these reasons it was of the opinion of the EERI experts to omit such vertical elements.

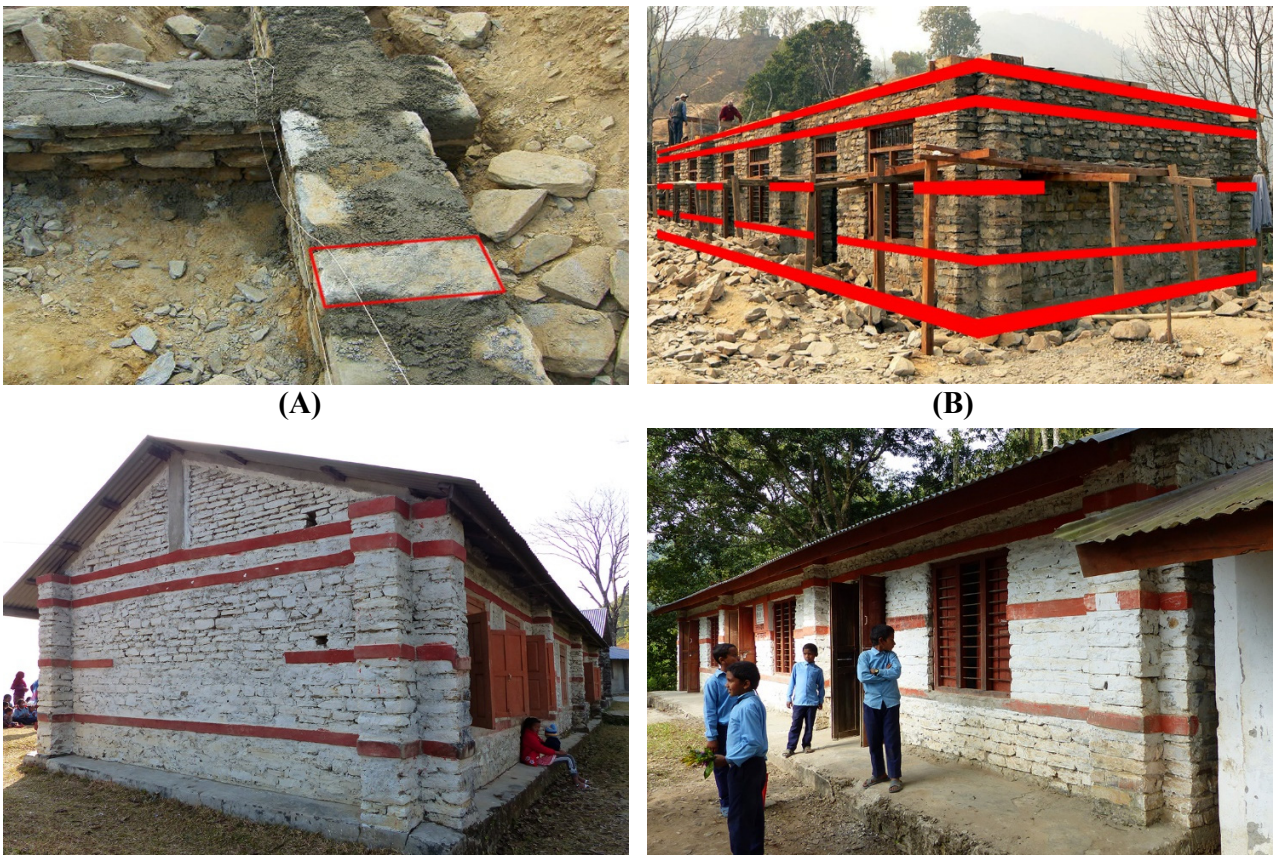
However, most codes and manuals require the installment of vertical bars and boxing around openings. When SSF studied this during the design of the schools in 2007, a considerable conflict came to light. For instance, the Indian and Nepalese "non-engineered" codes of practice of that time, show details of critical connection that requires a vertical steel bar, as well as a through-stone at the same position (IS.13828:1993 (2008); NBC 202:2015 (2015)). This is technically impossible, and the result is that important basic information is contradicting and open for interpretation. This conflicting set of details has become the starting point of the overall research, as it underlines the need for a better understanding and upgrading of the existing knowledge. The conflicting details are shown in **Figure 11**, as part of the review of technical manuals and codes in Chapter 2.

Based on the feedback from the EERI panel, it was decided not to install vertical reinforcement in the wall junctions and around the openings. Instead, they advised proper bonding in the masonry, the installment of many through-stones and the use of cement mortar as more important means of reinforcing the walls, as seen in **Figure 1A**.

Another basic and recurring question that needs further validation is the number of horizontal bands that are needed in rubble stone masonry walls. The consensus of the EERI team was to install horizontal reinforcements at five levels, being at plinth, sill, in-between stitches, lintel and top level, as shown in **Figure 1B.** After the 2015 Gorkha Earthquake, one expert reasoned that the horizontal beam below the openings, the sill beam, will be more efficient when installed at the halfway level of the masonry piers between the openings. This will further help in preventing the formation of shear cracks in these piers, instead of inserting in-between stitches at the junctions. However, the main purpose of horizontal beams is that they are continuous and thus contribute to the box behavior of the total building, as well as prevent out-of-plane failure of the walls. The plinth beam, lintel beam and top beam are such continuous elements. The sill beam under the windows, which is interrupted by doors, is semi-continuous, although it is expected that it still fulfills its purpose. But when positioning this beam at a higher level in the wall, it is interrupted by all windows, meaning that it is no longer a continuous element. The point to make here is that basic information about the number and position of these important elements has never been fully investigated nor validated.

As a side-benefit, it was predicted that the reduction of one horizontal band per story in masonry houses and schools would result in significant cost savings during the reconstruction effort in Nepal, where nearly a million buildings collapsed. This hypothesis has formed the basis of the in-depth cost analyses and comparisons in Chapter 4 of this thesis.

During the recent 2015 Gorkha Earthquakes in Nepal, all projects by SSF have performed well and survived the events with no significant damage. These projects are marked on the map of **Figure 17** in Chapter 4, and the nearest school was located just 40 kilometers away from the epicenter. Thorough inspections of the buildings showed that 9 out of 15 projects had not even suffered any cracks in the walls, while houses and older classrooms around them had collapsed. **Figures 1C,D** show the state of two schools in the villages of Mugri and Makaikhola in Kaski District of Nepal, which have sustained negligible to no damage at all. The pictures are taken in 2017, which is ten years after completion and two years after the devastating earthquakes. Their overall performance strengthens our belief that vertical reinforcements are unnecessary. But this hypothesis, together with further key questions about other standard elements such as the horizontal bands, buttresses and roof need to be validated. This has become one of the primary objectives of the overall research and the starting point of this dissertation.



(A) **(B)**

(C) **(D)**

***Figure 1**. Details of schools as constructed by SSF in Nepal including **(A)** walls with cement mortar, through stones but without vertical reinforcements, and **(B)** horizontal bands at five levels. Pictures of the undamaged state of the schools in **(C)** Mugri and **(D)** Makaikhola, after the 2015 Gorkha Earthquakes (courtesy of SSF).*

1.1.2 Context

All 15 reinforced schools that were built by SSF have withstood the 2015 Gorkha earthquakes without any significant damage. But in general, the figures show that rubble stone masonry structures do not behave well during a seismic event. Previous earthquake disasters, like in Kashmir (2005) and Nepal

(2015), resulted both in high casualties. Around 980,000 schools and houses were damaged and destroyed throughout Nepal, of which 80% took place in the rural areas. Here, 95% of all collapsed structures comprised low-strength rubble stone masonry, of which the majority was built with mud mortar (National Planning Commission, 2015). The primary reasons for the large-scale destruction are the lack of seismic-resilient features, and deficiencies in design, detailing, material and craftsmanship.

However, stone masonry using local skills and resources remains to be the predominant local structure in many developing countries in earthquake zones. Especially in the Himalayas, but also in many countries in Central Asia, the Middle East, Northern Africa and Eastern Europe, the technique is still being practiced today. The figures of **Table 1** demonstrate that most damage and devastation due to earthquakes usually takes place in developing countries, both in terms of casualties, and in terms of relative financial loss (Daniell et al, 2012). When looking at the loss of life in the 5 most recent events, 4 took place in a developing country (**Table 1A**, pointed out in **bold**), whereas in terms of economic losses, the complete top 5 occurred in developing countries (**Table 1B**, in **bold**). Therefore, a primary question we need to ask ourselves is: Have we done enough to reduce and minimalize the losses in these regions?

Table 1. *Casualties and economic loss figures of historic earthquakes since the 1900s.*

A. Loss of Life (highest estimated)

1	1976	Tangshan	China	655,000
2	1920	Haiyuan	China	273,400
3	**2004**	**Indian Ocean**	**Indonesia**	**227,898**
4	**2010**	**Haiti**	**Haiti**	**160,000**
5	1923	Great Kanto	Japan	142,807
6	1908	Messina	Italy	123,000
7	1948	Ashgabat	Turkmenistan	110,000
8	**2005**	**Kashmir**	**Pakistan**	**100,000**
9	**2008**	**Sichuan**	**China**	**87,586**
10	1970	Ancash	Peru	70,000
11	1935	Quetta	Pakistan	60,000
12	1990	Manjil-Rudbar	Iran	50,000
13	**2001**	**Bhuj**	**India**	**20,023**

Top 5 most recent in **bold;** 4 from 5 in **developing** countries (total 10 out of 13 (currently) in **developing** countries)

B. Economic Loss as Relative % of GDP

1	**1988**	**Spitak**	**Armenia**	**358.9**
2	1972	Managua	Nicaragua	105.0
3	1910	Cartago	Costa Rica	90.0
4	1906	San Francisco	USA	82.9
5	**2010**	**Haiti**	**Haiti**	**70.0**
6	**1993**	**Wallis/Futuna**	**Fiji**	**54.0**
7	1923	Great Kanto	Japan	52.8
8	1931	Nicaragua	Nicaragua	51.0
9	**1976**	**Guatemala**	**Guatemala**	**50.3**
10	**2015**	**Gorkha**	**Nepal**	**50.0**

Top 5 most recent in **bold**; all in **developing** countries (total 8 out of 10 in **developing** countries)

To answer that question, a good indicator is the amount of knowledge and number of research papers that have been presented at the 16 editions of the World Conference on Earthquake Engineering, between 1WCEE-1956 in California and 16WCEE-2017 in Santiago de Chile. Therefore, a review was carried out by the author of this thesis on the full proceedings of all conferences, as published on the website of National Information Centre of Earthquake Engineering (NICEE) at the Indian Institute of Technology Kanpur (NICEE, 2021). A specific search was conducted to trace any keynote speeches, state-of-the-art symposia, special or topic sessions and paper presentations, that address practical applications of "non-engineered" construction techniques for the developing context. This includes sessions and topics that specifically describe the design, construction, technical detailing and performance of techniques with local quality masonry materials such as bricks, stones and cement blocks, earthen structures such as rammed earth and adobe, natural materials such as wood, bamboo,

cane and grass, as well as masonry typologies such as unreinforced masonry (URM), nominally reinforced masonry (NRM) and confined masonry (CM).

The search further included design strategies in remote and rural areas, low-tech base isolation, retrofit solutions, as well as academic testing and modeling of local materials and "non-engineered", traditional and vernacular techniques. The search however excluded all topics related to historic overviews, risk assessments, mitigation strategies, fragility curves, policy making, seismic mapping and probabilistic seismic hazard analyses in the developing context; the review purely focused on technical, design and on-site practical related issues.

Table 2A-D shows in each first column the total number of keynote speeches and sessions that have been organized during the last 60 years, and in the second column those sessions that were specifically targeted for non-engineered techniques in developing countries (marked as n-E). The same is done for all published papers and poster presentations (**Table 2E-G**), and all total numbers are averaged in **Table 2H**. Overall, the table shows that roughly 1 percent of all content during 16 world conferences has targeted practical and technical applications in developing countries. This opposes the findings of **Table 1**, which shows that the damage is highest in those contexts.

Table 2. *Overview of 60 Years of "Non-Engineered" Topics at WCEE between 1956 and 2017.*

			A.		**B.**		**C.**		**D.**		**E.**	**F.**	**G.**	**H.**
			keynote speeches		**state-of-the art**		**special sessions**		**topics or sessions**		**total papers**	**gen.**	**n-E**	**%**
			Tot.	n-E	Tot.	n-E	Tot.	n-E	Tot.	n-E				
1st	USA	1956	1	0	-	-	-	-	5	0	38	0	0	0.0
2nd	Japan	1960	4	0	-	-	-	-	5	0	130	0	0	0.0
3rd	N-Zealand	1965	2	0	-	-	-	-	5	0	165	0	0	0.0
4th	Chile	1969	4	1	-	-	-	-	13	1	167	2	0	1.2
5th	Italy	1974	4	0	-	-	-	-	32	1	454	0	1	0.2
6th	India[1]	1977	4	1	-	-	-	-	12	0	657	0	1	0.2
7th	Turkey	1980	?	?	-	-	-	-	31	1	743	4	3	0.9
8th	USA	1984	5	0	-	-	-	-	58	1	859	5	0	0.6
9th	Japan	1988	3	0	18	0	25	0	57	0	1,002	9	0	0.9
10th	Spain	1992	3	0	36	0	11	0	77	1	1,151	8	1	0.8
11th	Mexico	1996	2	0	24	0	18	1	105	0	1,602	15	1	1.0
12th	N-Zealand	2000	0	0	11	2	10	1	-	-	1,744	12	2	0.8
13th	N-Zealand	2004	11	1	-	-	15	1	107	1	2,341	20	9	1.2
14th	China	2008	11	0	-	-	37	2	23	1	3,012	21	4	0.8
15th	Portugal	2012	9	1	8	0	17	0	83	2	3,344	30	10	1.2
16th	Chile	2017	9	0	-	-	76	2	-	-	2,131	32	9	1.9
Total sessions / papers			72	4	97	2	209	7	613	9	19,540	158	41	**1.0**
		%		**5.6**		**2.1**		**3.3**		**1.5**		**0.8**	**0.2**	

A. and B.	Includes any topic related to developing countries, no topics excluded
C. D. F. and G.	Includes any technical topic related to "non-engineered" construction in developing countries, including retrofit, but excluding damage reports, risk reduction strategies, policy making, seismic mapping etcetera
E.	Total number of papers and poster presentations at each conference
G. (n-E)	Papers that specifically address technical and practical topics related to "non-engineered" construction
H.	Percentage of columns F. and G. combined
[1]	First appeal ever for "non-engineered" construction techniques, by Prof. A.S. Arya

1.1.3 Housing Census Data for Rubble Stone Masonry

To gain insight into the current building practices and needs regarding stone masonry, housing census data was retrieved and compared from countries where the technique is still abundantly practiced. In some cases the construction data is unavailable or non-existent, for instance in Afghanistan. Decades of conflict and instability made it impossible to conduct a national population and housing census since 1979 (CSO, 2018). Turkey and Croatia have not included detailed data on construction types in their census reports. Iran carries out a population and housing census every 5 years, but only differs between "reinforced concrete, metal skeletons and others" regarding the supporting system of residential units (SCI, 2018). In China, the 2000 census divided housing typologies by wall materials, in just four categories being "steel & reinforced concrete, brick & stone, wood & bamboo, and others" (NBS, 2000). Unfortunately, no distinction is made between urban and rural settings, which could have indicated the differences between bricks and stone in the Himalayan provinces. In the 2011 census the categories were changed to "steel & reinforced concrete, mixed structures, brick & wood and others", therefore it is not possible to derive or compare numbers for stone masonry in China (NBS, 2011).

However, significant data was found for the Himalayan region. The Nepali census of 2001 has divided all residential units into "Pakki (permanent), Ardha Pakki (semi-permanent), Kachchi (temporary) and others". The first category refers to units where the walls and roof are constructed with "permanent construction material like cement, bonded brick, concrete, stone, slate, tile, galvanized sheet etcetera" (CBS, 2003). In the 2011 census, over 5.4 million housing units are divided by wall type, where a first division is made between urban (19.3%) and rural (80.7%) houses. However, all masonry units such as bricks, blocks and stones are grouped together and are distinguished by type of mortar, being mud-bonded or cement-bonded (CBS, 2012). After the 2015 Gorkha Earthquakes, it was estimated that over 80% of all building damage took place in the rural areas, where 95% of all collapsed structures comprised low-strength rubble stone masonry, of which the majority was built with mud mortar (National Planning Commission, 2015). It is also the personal experience of Schildkamp that most rural masonry construction in Nepal comprises stone masonry, simply due to the unavailability of bricks and concrete blocks at further distances into the mountain areas. For that reason, it is assumed that the census numbers for masonry are mainly made up of rubble stone masonry with either mud mortar (47.1%) or cement mortar (19.0%), totaling 66.1% or nearly 2.9 million housing units (**Figure 2A**), whereas numbers for bricks and blocks are negligible in the rural regions.

The last census in Pakistan dates from 1998, but it shows separate numbers for stone masonry units at 5.13% of the total housing stock, resulting in 811,478 stone houses on the national scale. More interesting is the division by wall materials, which shows high ratios of stone masonry in the highest seismic zones 3 (27%) and zone 4 (21%). Both zones include the northern mountainous provinces, although no difference is made between the urban and rural context or types of mortars (Ahmed et al, 2014). The data for zone 3 covers a significant area in the north of Pakistan (**Figure 2B**).

Tajikistan is divided into four provinces, but stone masonry plays no significant role in three of them, except in the Gorno-Badakhshan Autonomous Region which is located in the Pamir Mountains. The name Gorno-Badakhstan is Russian and means "mountainous Badakhstan", and whilst covering over 40% of the land area of the country, it represents 3% of its population only. Although sparsely inhabited, 71% of all housing units are constructed in stone masonry (**Figure 2C**). A total of 28,210 houses were included in the 2010 Population and Housing Census, of which 20,067 units were

constructed in stone, which was further categorized as "shell rock, sandstone, limestone, tuff, rubble or ceramic stone, etc." but without mention of the mortar type (Tajstat, 2013).

The 2005 census of Bhutan (Office of the Census Commissioner, 2006) has combined the wall types of concrete, bricks and stone into one category, which therefore cannot be compared with the 2017 census data which is more detailed (NSB, 2018). Here, in total 163,001 housing units are assessed, of which 102,607 (62.9%) are in rural areas. Stone masonry represents 13.4% of the urban housing stock and 42.0% of the rural housing stock (**Figure 2D**), where the latter is further broken down in 36,254 units in mud mortar (35.3%) and 6,837 units in stone with lime or cement mortar (6.7%).

The last census in India of 2011 distinguishes between the rural and urban situation. There are two categories of stone masonry included, one is mortarless and the other with any type of mortar. Both types are combined in **Figure 2E**, resulting in the use of 13.7% of stone masonry in rural India, 15% in urban areas (not in the figure), and 14.1% overall (**Figure 2H**). Of particular interest is that comparable data was found in the Indian housing censuses of 1991, 2001 and 2011 (**Figure 2F-H**). Currently, stone masonry is banned in most seismically prone countries because of weak performance in past earthquakes, therefore it is generally assumed that the technique is less practiced these days. However, **Figure 2H** shows a significant rise of stone masonry in the 2011 census, compared to both 2001 and 1991. In the urban setting the numbers more than doubled, from 7.2% in 2001 to 15.0% in 2011 (not in the figure). In absolute numbers, the total number of Indian housing units in stone masonry amounted to over 34.8 million. It is further noted that in the rural areas, the vast majority (roughly 95%) of all wall materials can be classified as "non-engineered techniques", mainly masonry with bricks, stones and mud blocks, as well as construction with wood and bamboo (**Figure 2E**). The same can be concluded for rural Nepal, Pakistan, Tajikistan and Bhutan as well (**Figure 2A-D**).

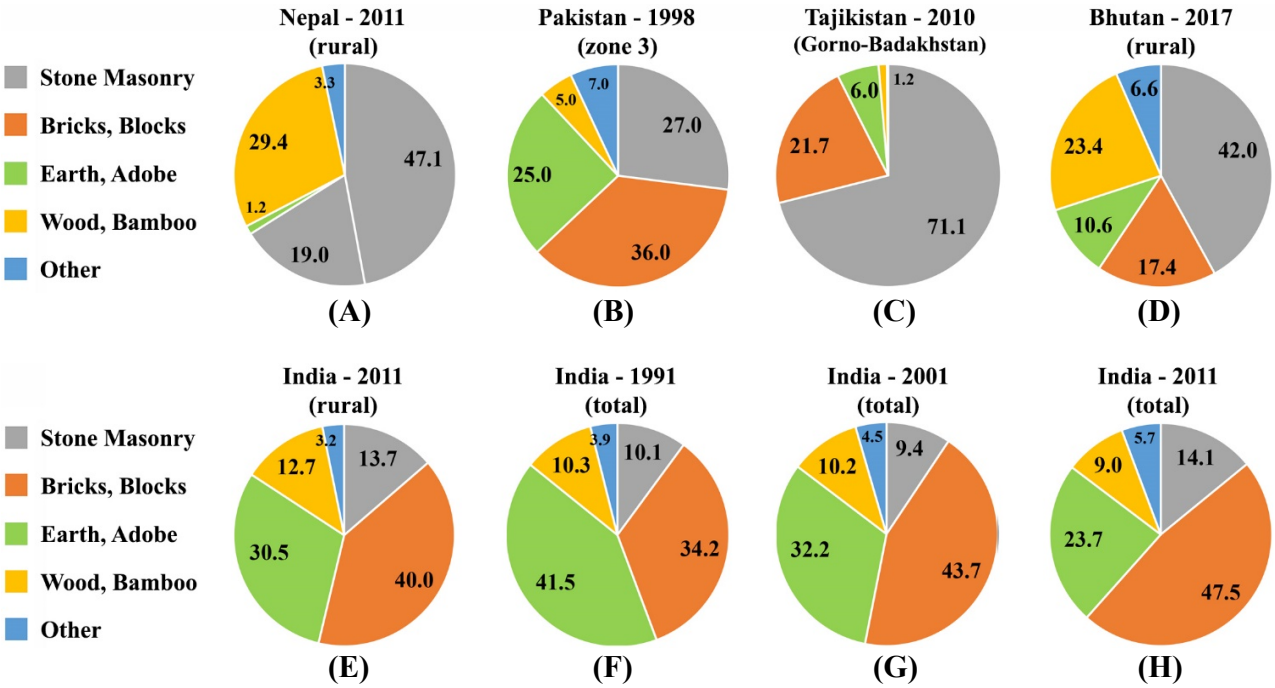


***Figure 2**. Housing census data for rubble stone masonry residential units:**(A-E)** for rural areas in Nepal, Pakistan (zone 3), Tajikistan, Bhutan and India; **(F-G)** comparison in India between 1991, 2001 and 2011.*

If, similar to India, we assume that the numbers of stone masonry housing units have not been reduced in the other Himalayan countries as well, but remained stable at the least, this results in a current housing stock of roughly 39.5 million units in stone masonry. This includes either dry-stacked masonry, or masonry with mud or cement mortar, in both the rural and urban settings. With an average household number of 5.5 members in rural areas (based on an average of around 4 to 5 members in Nepal and India, up to 6 to 7 in Pakistan and Tajikistan (PRB, 2021)), stone masonry houses directly affect the lives of 217 million people in the Himalayan region alone. This number is without consideration of the bordering regions of China and Afghanistan, due to lack of recent information. But when considering these and other seismically active regions where stone masonry is still practiced, such as in Yemen, Iran, Turkey, Algeria and Georgia (to name a few), the research work may easily address an additional target group of several hundreds of millions of people worldwide.

1.1.4 State-of-the-Art

The previous sections show that there is a significant imbalance between the seismic construction needs in rural and remote areas in developing countries, compared to the level of effort that has been undertaken to improve the overall knowledge in such contexts. Therefore, we must ask ourselves the following key questions: Have we done enough to reduce and minimalize the losses in these regions, in which the devastation is usually highest after earthquakes? Are we offering reliable technical and practical solutions to all stakeholders, from the homeowners and self-builders to the aid industry and governmental bodies? Are we satisfied with the overall existing levels of practical and technical knowledge and information? If the answers to these questions are negative, then the obvious question is: How can we improve this situation?

Valuable work has been carried out over the years, but the available knowledge is largely based on empirical evidence that comes from just a handful of publications from the 1980s. These have not been updated since, and the knowledge has not advanced much in the past 40 to 50 years. It was already noted in 1977 that "a review of the earthquake codes of various countries shows that much of the information is empirically based and not theoretically derived. In that respect, the recommendations must be subject to continuous review and change as more data become available" (Arya, 1977). Furthermore, Bertero and Bertero (2002) state that "codes and standards should be simple enough so that they can be applied effectively according to the education (knowledge) of the professionals involved (designers, builders, governmental bodies) as well as the owners, but without compromising the reliability of the structure. (…) Codes should reflect the most reliable procedures that can be developed according to the state-of-the-art in seismic engineering."

Effectively, for "non-engineered" structures this has not been undertaken as of date, for understandable reasons. One important reason is that vernacular building types include many variables which are highly dependent on site-specific parameters for local construction quality, materials and workmanship. Such variables are difficult to determine and quantify, whereas from an engineering perspective such variables are not integrated in calculations and models. As of today, a methodology that includes locally sourced parameters is non-existent.

Currently, the existing knowledge highly depends on design specifications and construction guidelines that are based on general rules of thumb, often referred to as "best practice" and "building back better" strategies, but with no reference, value or set standard of what "best practice" means. As a result, basic questions such as the required number of beams, correct positioning of buttresses, or the need for

vertical steel reinforcements have seldom surpassed the level of assumption and opinion. In-depth justification or scientific validation of how these elements work and behave during a seismic event are basically not present for any non-engineered construction type. For the specific typology of rubble stone masonry in seismic areas, a complete and validated overview has never been presented before. In-depth and detailed technical reviews of practical manuals have not been performed, and costing data is virtually non-existent. Seismic code assessments with calculated examples for rubble stone masonry buildings have not been carried out.

As a result, the information in the codes, technical regulations and practical manuals is largely outdated, contains many contradictions, and has become ambiguous. This raises questions about the completeness and correctness, as well as about the reliability and actual value of this knowledge.

1.2 Objectives of the Research

1.2.1 Overall Research Objective

To address any shortcomings, a research initiative is started by the name of SMARTnet, which stands for **S**eismic **M**ethodologies for **A**pplied **R**esearch and **T**esting of **n**on-**e**ngineered **t**echniques. The overall objective of SMARTnet aims for i) a better understanding of the seismic behaviour, ii) a prediction of the seismic resilience, and iii) an overall improvement of "non-engineered" traditional and vernacular techniques in general, and of stone masonry buildings with low-strength cement mortars in particular. A second aim is to make this knowledge understandable and available for engineers and non-engineers across the globe.

The strategy of SMARTnet envisions a joint and multi-disciplinary approach of global collaboration, to fully assess, validate, optimize and complement the existing knowledge of non-engineered techniques, by means of the current state-of-the-art for calculating, testing and modeling. A further aim is to cope with the massive number of material variables and to generate cross-checked data that can be used for calculations and computer modeling of non-engineered techniques. The time has come for "Non-Engineered 2.0".

1.2.2 Research Objectives of the Thesis

This thesis is the starting point and addition toward the overall objectives of SMARTnet as described in the previous section. The outcomes presented in this research work cover various aspects of the seismic demand determination of rubble stone masonry buildings in seismic areas, thus representing the halfway point of the overall research agenda. The core of this thesis is divided into three main parts.

The first part is a global review of the state-of-the-art regarding the knowledge levels of rubble stone masonry buildings in seismic areas. This part covers both practical field manuals and national seismic and masonry codes, which will be read and assessed in their original languages with the help of native-speaking experts. Every aspect of the design and construction sequences will be analyzed, with primary attention to the local practices in regions where the technique is still applicable.

The second part analyzes detailed and localized cost comparisons of the earthquake-resistant elements in masonry structures, to give insight into the additional costing between an unreinforced and a nominally reinforced building. This is based on unique local costing data in Nepal, spanning ten years.

The third part works toward the development of practical applications and structural solutions. It includes comparative reviews and a complete analysis of the base shear formulas of nine selected countries, with base shear seismic demand calculation examples as performed on two case study buildings. The national codes are read in original languages and applied literally; what the code dictates is what we use and report.

The reviews, comparison and calculations aim to generate a complete and detailed overview of similarities, contradictions and gaps in the existing knowledge. It will also highlight the state-of-the-art of the applicability, useability, and shortcomings of the currently available information and methodologies. Then we can accurately determine where we stand today and how the knowledge is perceived. This is an important step toward international acknowledgement of the current situation, that may serve as a starting point to address any needs for adjustment and improvement.

1.2.3 Research Questions of the Thesis

All three parts together address the primary research objective of this thesis as formulated below, and which is further broken down in the following additional research questions:

What is the state-of-the-art of practical seismic applications and seismic code provisions for nominally reinforced rubble stone masonry buildings with cement mortar?

1) What is the current state and value of the existing design and practical field manuals, in terms of reliability, applicability, usefulness and completeness?

2) What are the original sources of all the existing knowledge, when were they last updated and what is their current status?

3) Which countries in the world currently allow the application of the technique according to their national seismic and masonry codes, and is there a consensus on the global design and construction requirements?

4) What are the cost implications of different solutions for the foundation, walls and roofing system in "non-engineered" seismic design?

5) What is the cost difference between a traditional unreinforced school building, and a fully reinforced design with the addition of seismic reinforcing features?

6) Which country is the most conservative or the most tolerant regarding the base shear seismic demand, by following Equivalent Lateral Force-principles for Ultimate Limit State verifications, based on the literal application of their respective seismic codes?

7) Are the national seismic codes applicable for heavy stone masonry buildings, and is there a need to develop different or more appropriate concepts for analysis and calculation, as well as validation of key parameters?

1.2.4 Research Limitations of the Thesis

The research in this thesis limits itself to the determination of the seismic demand and all the analyses, comparisons and calculations that are related to this phase. The determination of the base shear seismic demands is restricted to calculations by hand and with spreadsheets. We choose to do this to stay true to the spirit of a "simplified and non-engineered" approach. A further reason is that at this stage, cross-checking through numerical modeling and verifications will be based on too many assumptions that will not allow for indisputable conclusions.

It is assumed that the seismic demand phase roughly marks the halfway point of the overall research objective of the complete SMARTnet project.

This thesis does not cover the continuation phase of the seismic capacity verifications, such as strength and displacement calculations of the masonry buildings, the wall panels and the flexible diaphragms. This phase highly depends on the appropriate application and interpretation of numerical models. Which heavily relies on the determination of realistic and reliable mechanical properties of rubble stone masonry with cement mortar. These are currently non-existent and therefore the seismic capacity checks fall outside the scope of this thesis and will be performed through future research.

1.3 Outline of the Thesis

The research outlines and results in this dissertation are described in 6 chapters, starting with the Introduction in this current Chapter 1.

Chapter 2 defines specific search criteria and definitions for schools with loadbearing walls that are built with rubble stone masonry in cement mortar, which are nominally tied with horizontal reinforcements. Following these criteria, 47 relevant field manuals between 1972 and 2017 as well as 2 "non-engineered" seismic codes have been analyzed and compared. An overview is created that shows the similarities, contradictions, gaps and differences between the publications.

Chapter 3 builds upon the same criteria as set in chapter 2 and analyzes nearly 325 national seismic and masonry codes from all over the world, of countries where stone masonry was, or still is, abundantly practiced. It compares and summarizes design specifications and construction requirements for both houses and schools, which will be used for the determination of the base shear seismic demand comparisons of 9 selected countries, in Chapter 5.

Chapter 4 analyzes the cost breakdown of earthquake-resistant mountain schools in Kaski District of Nepal, as built by Smart Shelter Foundation with the techniques of rubble stone masonry and hollow concrete block masonry. This includes a post-disaster check of possible price hikes after the 2015 Gorkha Earthquake in Nepal, and the preparation of a rapid cost-estimation tool for different configurations of school buildings.

Chapter 5 performs full base shear seismic demand analyses and calculations on two nominally reinforced rubble stone masonry house and school designs, according to the national seismic codes of Nepal, India, Pakistan, Afghanistan, China, Tajikistan, Iran, Turkey and Croatia. It compares the base shear formulas and the inertia forces distributions according to these codes, as well as material

densities, seismic weights, seismic zoning, natural periods of vibration, response spectra, importance factors and seismic load combinations. Then, by following Equivalent Lateral Force-principles for Ultimate Limit State verifications ($10\%PE_{50y}$), the base shear and story shears are calculated for a design PGA of 0.20g, as well as the effects of critical load combinations on the Axial Forces (*N*), Shear Forces (*V*) and Bending Moments (*M*).

Chapter 6 is the conclusion which summarizes the main findings of the overall research and discusses possible solutions and suggestions for improvement. An introduction to future research is made, and an international appeal is placed to experts, academics and final-year students worldwide, to exchange their knowledge and to support the project with their time and expertise.

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Chapter 2

School Buildings in Rubble Stone Masonry with Cement Mortar in Seismic Areas: Literature Review of Technical Norms and Practical Manuals

Summary

In 2018, a literature review has been carried out as a first step to determine the current state-of-the-art regarding non-engineered stone masonry school buildings in seismic areas. Specific search criteria and definitions were determined for schools with loadbearing walls that are built with rubble stone masonry in cement mortar, which are nominally tied with horizontal reinforcements. A total of 47 relevant field manuals between 1972 and 2017 as well as 2 "non-engineered" seismic codes have been analyzed and compared, of which an overview is created that shows the similarities, contradictions, gaps and differences between the publications.

Only 9 manuals describe design and construction processes for schools, even though this conflicts with the related codes which prohibit the use of stone masonry for buildings with importance factor 1.5 or higher. It was noticed that 7 out of 9 manuals are (co-)written by the same author, and that the available knowledge, which is largely based on empirical evidence, can be traced back to just a few main sources. However, no consistency nor consensus was found on almost all key topics, such as main dimensions, openings and reinforcing elements. Also, the same illustrations and tables are copied over and over again, including apparent conflicts between the details. The fact that this has never been rectified, are indications that the knowledge has not evolved much since the 1980s.

It is concluded that the available information in the technical and practical field manuals contains many contradictions and has become ambiguous. This raises questions about the correctness, reliability and actual value of the knowledge. To further investigate this hypothesis, the search criteria and findings of this chapter are taken as the starting point of the next chapter, which reviews the state-of-the-art and requirements of national seismic and masonry codes.

2.1 Introduction

Between 2007-2012 the Dutch non-for-profit organization Smart Shelter Foundation (SSF), together with local partner SEED Foundation, executed several earthquake-resistant schools in rubble stone masonry in Nepal. The designs were made by Martijn Schildkamp, architect and author of this thesis, by following general rules of thumb. These rules were obtained from the numerous technical guidelines and practical manuals that can be found online, and which are commonly referred to as "best practice" or "non-engineered construction principles" (Schildkamp, 2015a). The term "non-engineered" in construction refers to buildings as "those which are spontaneously and informally constructed in various countries in the traditional manner, without any or little intervention by qualified architects and engineers in their design" (Arya, 2000). While studying the available knowledge, it was the personal experience of Schildkamp that the information was often unclear, contradictory and incomplete. Further into the process, during the design and construction phases of the projects, many technical questions and practical issues came to light, as highlighted in Chapter 1.

This chapter undertakes a literature review of 47 practical manuals and 2 seismic codes, to determine the state-of-the-art regarding rubble stone masonry school construction in seismically prone developing countries. No comparable studies were found, as it is the first time that a literature review of technical guides and construction manuals has been compiled on this subject matter. The focus is on the available technical and practical field manuals, whereas requirements as dictated in the national codes are addressed separately in the next chapter. This review aims to summarize the generalities, similarities, contradictions and discrepancies, as well as any need for further validation, optimization and complementation of the existing knowledge. It further aims to determine the applicability and reliability of existing publications, and to understand the need for revision of the existing knowledge. In this chapter all possible design requirements, construction details and practical implications are described and compared, resulting in a complete overview of all the necessary steps toward completion of a "non-engineered" school construction project. The following elements are reviewed:

- Building typology
- Types of stone unit, mortar and stone masonry
- Overall building dimensions
- Foundation
- Wall specifications, masonry patterns and detailing
- Openings in walls
- Horizontal and vertical reinforcements
- Roof structure

The schools as built by SSF in Nepal are taken as the reference for the following reviews, as shown in **Figure 3**. Although Nepal has officially adopted the Metric System (Government of Nepal, 1968), most villages still use the Imperial System and therefore the drawings are expressed in feet (') and inches ("). All units in this chapter however follow the SI metric system such as meter (m) and millimeter (mm). The schools are designed and constructed as follows:

- The classrooms have a maximum interior floor plan of 4.8x4.8m (16.0'x16.0'), **Figure 3A**. The dimensions of the building volume do not exceed the maximum ratio of width versus depth of 1 : 3. This translates to maximum 3 classrooms in a row, or else a separation gap is introduced of 75mm (3") between the volumes.

- A stepped strip foundation in rubble stone masonry with cement-sand mortar is placed on a plain concrete screed, on top of a layer of rough boulders. The top of the foundation including tie beam is raised 450mm (1'-6") above ground level (**Figure 3E**).

- The walls consist of 350mm (1'-2") thick random rubble stone masonry in cement-sand mortar, with buttresses at all wall ends. The walls have a maximum height of 2.6m (8'-6"), from the top of the foundation beam to the top of the wall. The mountain stones are not dressed, but regularly sized stones are chosen and placed in courses as consistent as possible. The masonry includes many bond stones that are placed over the entire thickness of the wall, to decrease the risk of delamination of the wythes.

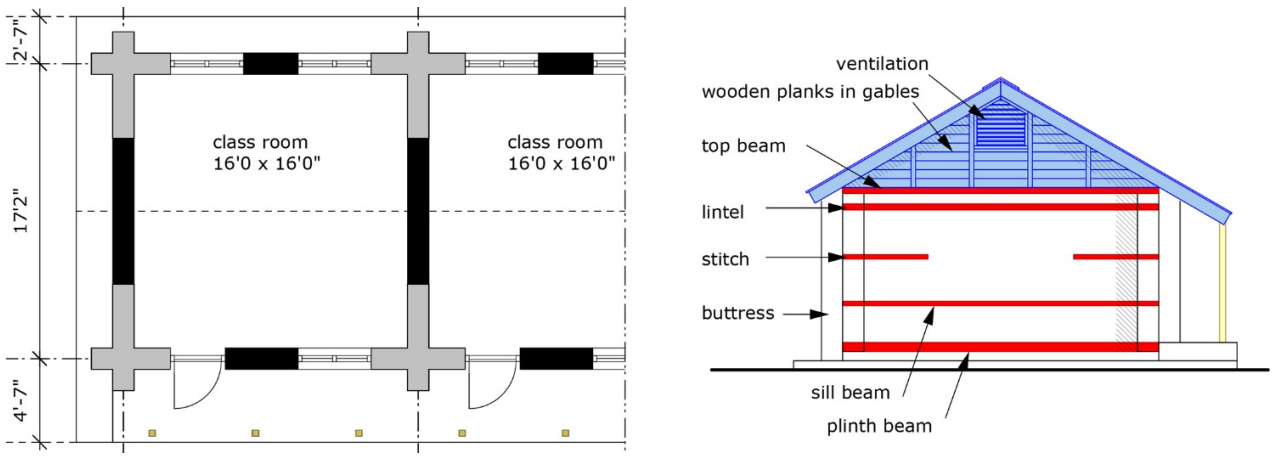
- The total combined width of openings does not exceed more than 50% of the length of a wall panel, with a minimum distance between inside of the corner and opening, as well as a minimum width for piers between openings, of 600mm (2'-0"). The doors open to the outside for safe exit during an emergency.

- As the schools are located in a high seismic zone, the walls are tied together with horizontal bands made of reinforced concrete at five different levels in height, **Figure 3B**. These are i) a continuous plinth beam on the foundation, and ii) a sill band under the windows which is semi-continuous as it is interrupted by the doors; iii) in-between stitches in the corners and T-sections break the height between sill; iv) the most important lintel beam, that runs over all door and window openings, and v) same as the lintel, the top beam is also fully continuous. Different thicknesses of the beams, as well as different numbers and diameters for the steel reinforcements were used.

- Other than stone masonry buttresses, no vertical reinforcements are incorporated in the critical wall connections, such as at the corners, t-sections and around openings, as it was reasoned that the limited amount of steel will not provide the desired amount of ductility. Also, the steel will disrupt the masonry bonding in these critical connections, which possibly makes these weaker rather than stronger, and therefore may create more problems than benefits. However, this remains to be a highly debated subject among the experts (and is basically the reason and starting point of all upcoming in-depth research). The need for vertical reinforcements will be discussed further on in this chapter.

- Instead of heavy masonry gables that have the risk of toppling during an earthquake, wooden trusses are placed on all interior and on the end walls, and then closed with wooden planks with openings for cross-ventilation. Further trusses are placed at intermediate points which are inter-connected with cross-bracing elements and purlins, and a stiff ceiling is placed underneath. This way the roof structure acts as one, thus enhancing the box action of the total building. Around 2007, big bolts were not available in the local markets, so strands of 4mm galvanized steel wire were cast into the top beam to firmly connect the wooden trusses to the walls.

- To guarantee a high construction quality, much emphasis was put on the training and supervision of the local laborers during the construction process, following the practical principles as described in Schildkamp (2015b). Much emphasis was put on the use of correct materials, preparation of proper mixes for mortars and concretes, and detailing of steel reinforcements. After completion of the building, all earthquake-resistant measures were painted on the outside of the building, with explanation in Nepali text, so that the building becomes a full-size billboard for earthquake-resistant construction.



(A) **(B)**

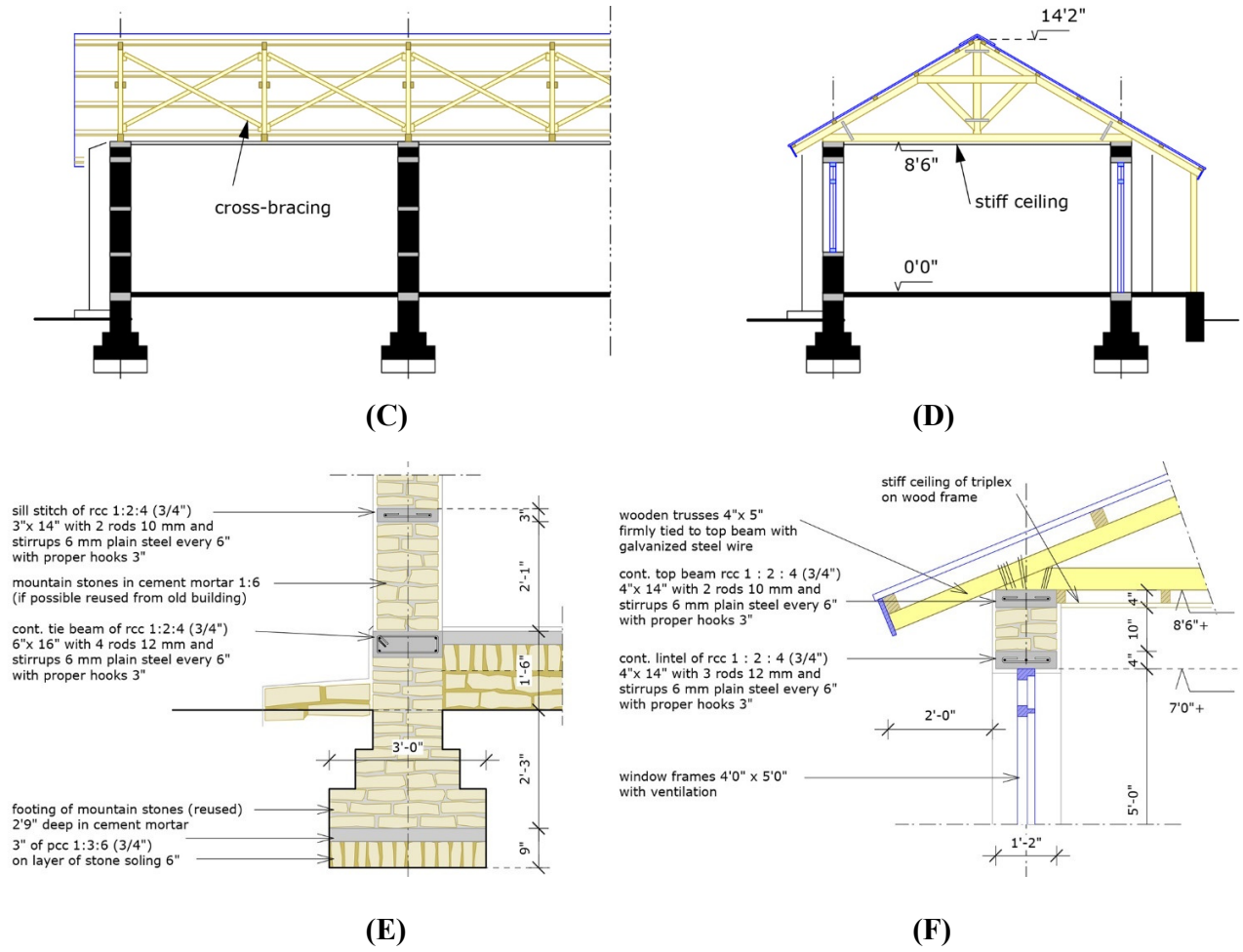


Figure 3. *(A) School plan in rubble stone masonry and* ***(B)*** *Side elevation with horizontal reinforcements and buttresses.* ***(C)*** *and* ***(D)*** *Cross-sections over building.* ***(E)*** *Detail of foundation, floor and wall in rubble stone masonry, and* ***(F)*** *Detail of window, wall and roof connection (all by courtesy of Smart Shelter Foundation).*

2.2 Definitions and Search criteria

This section defines the search criteria for the literature reviews of the technical writings and practical field construction manuals in Chapter 2, as well as for the review of national seismic and masonry codes in the next Chapter 3. Some further parameters are included about the different types of publications and their content, to determine the usefulness and eligibility of the knowledge.

2.2.1 Types of Stones and Stone Masonry

Stone as a material can be categorized into numerous typologies, but in terms of stone masonry it can essentially be brought back to two major categories which depend on the specifications of the stone units, such as shape and dimension: Rubble stone and Ashlar. Rubble stone units may refer to round river boulders (**Figure 4A**), and to field or mountain stones of irregular shape that are uncut, unevenly

split, unsquared and un-dimensioned. These are either randomly stacked (**Figure 4B**) or "brought to courses" (**Figure 4C**). When stones that are cut, squared and dimensioned into a regular sized parallelepiped shapes it is called Ashlar, also known as cut, squared or dressed stone (**Figure 4D**). To cut such neat units by hand involves lots of intensive labor, which is highly dependent on the hardness of the stone and the required level of shaping and finishing. This makes Ashlar much more expensive than rubble stone and it is therefore less often used in the rural areas.

The shape of the stone is important for the structural stability of the wall. Generally said, the rounder the boulder, or the more irregular the shape of the rock, the more difficult it is to build a consistent and stable wall. A distinction is made between uncoursed or coursed stone masonry, and the strength of a wall is further influenced by the way the stone units are laid, such as the detailing of corners and junctions, the bonding patterns, overlapping and interlocking of the units, and the thickness and continuity of the joints.

(A) **(B)** **(C)** **(D)**

Figure 4. (A) *Round river boulders with mud mortar.* ***(B)*** *Random rubble stone masonry with mud mortar.* ***(C)*** *Random rubble stone masonry brought to courses with cement mortar.* ***(D)*** *Ashlar stone masonry with lime-sand mortar (all by courtesy of Smart Shelter Foundation).*

2.2.2 Types of Mortar

Of equal importance is the type of masonry mortar that is used, as it has a huge impact on the strength characteristics of the masonry. Mud is the main choice in the rural and remote areas in most developing countries, followed by cement mortar if the people can afford it, or lime-sand mortar if lime is available, although this is not very common in remote regions such as the Himalayas. Mortar-less masonry, as used in parts of Pakistan and India, behaves much different in an earthquake compared to mortared walls (Carabbio et al, 2018) and therefore dry-stacked stone masonry falls outside the scope of this review. No publications or literature was found about the use of stabilized mud mortar in seismic areas.

However, it must be emphasized that mud mortar does not perform well in earthquakes, as was painfully shown after the 2015 Gorkha Earthquakes in Nepal. It is estimated that nearly 1,000,000 houses and 57,000 classrooms were destroyed and damaged throughout the country (PDRF, 2016). It is further estimated that 81% of all building damage took place in the rural areas, where 95% of all collapsed structures consisted of low-strength masonry; the majority being stone with mud mortar (NPC, 2015). Due to limited finance and access to resources it is expected that the vast majority of these will be rebuilt in stone masonry again. Given the widespread damage, the focus of this review and overall research is on validating rubble stone masonry with cement-sand mortar.

By combining stone unit and mortar type, Arya (2003) grades stone masonry in six classes relative to its seismic safety, thus placing the schools of Smart Shelter Foundation in the second grade, **Table 3**.

Table 3. *Grading of stone masonry types according to Arya (2003).*

	pattern	masonry type	mortar type	safety level
i)	random	rubble stone masonry	in mud mortar	sixth
ii)	coursed	rubble stone masonry	in mud mortar	fifth
iii)	dressed	Ashlar masonry	in mud mortar	fourth
iv)	random	rubble stone masonry	in cement mortar	third
iv)	coursed	rubble stone masonry	in cement mortar	second
vi)	dressed	Ashlar masonry	in cement mortar	first

2.2.3 Types of Loadbearing Masonry Systems

A distinction is made between three important different typologies of load-bearing masonry systems, which are reinforced masonry (RM), confined masonry (CM) and unreinforced masonry (URM), as follows:

- Reinforced masonry has regular horizontal and/or vertical reinforcements throughout the wall which are embedded in such way, that they act together with the masonry units in resisting the lateral forces in both in-plane and out-of-plane directions. RM must be designed and calculated by engineers and is therefore categorized as an "engineered" construction technique.

- Confined masonry walls act as shear panels which serve as the lateral load-bearing system. These walls are built first, usually with a toothed pattern at the wall ends, and then tie-beams and tie-columns of reinforced concrete are cast around the panels, serving as confining members. Ashlar stone units certainly qualify for confined masonry, but likely due to the high cost of these, no references were found of CM with Ashlar stones. Regarding confined rubble stone masonry, only one experimental study was found, which shows benefits of using confining elements for the improvement of in-plane strength and ductility of the stone masonry walls (Ahmadizadeh and Shakib, 2015).

- Unreinforced masonry has, as the name implies, no reinforcements whatsoever incorporated in the walls. Almost all seismic codes worldwide prohibit the use of URM in earthquake zones, unless "additional requirements for unreinforced masonry are in place" (Eurocode 8, 2004), such as concrete beams or steel ties. However, this makes the term "unreinforced" somewhat ambiguous, for these buildings can no longer be classified as purely URM, whereas it is not RM either since the reinforcements merely tie the walls together. **Figure 5** shows such an example of a school building in a highly seismic zone in Nepal, where the rubble stone walls are strengthened by using cement mortar and the addition of buttresses and horizontal reinforced concrete beams. Also, the laying of the stones in the masonry itself is "brought to courses."

2.2.4 International Adoption of Nominally Reinforced Masonry (NRM)

The recently developed Multi-Hazard Building Taxonomy GED4ALL (Silva et al, 2018) "enables the user to describe a building by assigning characteristics relevant to its structural response under multi-hazard actions." One important attribute is the material of the lateral load-resting system, which for masonry is divided into unreinforced (MUR), confined (MCF) and reinforced (MR). Another important

attribute is the ductility of the system, divided into "no, low, moderate and high ductility." As this would classify the examples in **Figure 5** and **Figure 12** as "unreinforced masonry with low ductility", or "URM with additional reinforcements", it raises the question whether a fourth category should be introduced to further avoid confusion. Furthermore, Confined Masonry is often described as "semi-reinforced masonry", a term that also applies to loadbearing walls with horizontal bands, although both systems structurally behave very different. To enhance clarity, this thesis calls for the introduction of a new and fourth category of masonry and proposes the international adoption of the term "Nominally Reinforced Masonry" (NRM) for walls that are nominally strengthened; next to the existing types of URM, CM and RM.

Figure 5. *School building in Nepal with rubble stone masonry in cement mortar that is brought to courses, and with nominal horizontal reinforcements (by courtesy of Smart Shelter Foundation).*

2.2.5 Engineered versus Non-Engineered

During the 12th World Conference on Earthquake Engineering in New Zealand, Professor A.S. Arya presented the often-quoted definition for non-engineered buildings as "those which are spontaneously and informally constructed in various countries in the traditional manner, without any or little intervention by qualified architects and engineers in their design" (Arya, 2000). The first time an appeal was made for the development of separate seismic codes for "unengineered buildings" is by Arya (1977) during the 6th World Conference on Earthquake Engineering in New Delhi in 1977. Due to differences between developed, developing and underdeveloped economies, as well as between rural and urban contexts, he concluded that two types of code specifications were required; one for engineered buildings and one for non-engineered traditional constructions. A workgroup was formed that included Professors Arya from India and seismic engineer Boen from Indonesia, who may be regarded as the pioneers of researching the seismic behavior of non-engineered techniques. The outcome was the first official guideline fully dedicated to non-engineered construction named "Basic Concepts, part 2: Non-Engineered Construction" (Arya et al, 1980), which was further developed into the well-known "Guidelines for Earthquake Resistant Construction of Non-Engineered Construction", published by the International Association for Earthquake Engineering (IAEE) firstly in 1986 (Arya et al, 1986), and revised in 2004 (IAEE, 2004) and 2014 (Arya et al, 2014).

Reinforced masonry needs to be designed and calculated by engineers and is therefore categorized as an engineered construction technique. Unreinforced masonry on the other hand, such as stone masonry which is still commonly used in many regions in the world, is often referred to as a non-engineered construction type. Whether non-engineers should be involved in earthquake-resistant construction of unreinforced and/or nominally reinforced masonry structures is a question on its own, but fact is that engineers are seldom available in the rural areas in developing countries. For that reason, many practical manuals are directly targeting the non-engineered user groups. All building, seismic and masonry codes are per definition engineered publications, as these are meant for qualified engineers and architects, and not for the general public. Publications that introduce detailed explanations and equations about design spectra, dynamic response and base shear forces, such as in Arya (1987a), Tomazevic (1999) and Indian Railways (2017), are also not written for readers without engineering background. On the other hand, design guidelines, technical manuals and on-site construction booklets, from now on referred to as "practical manuals", may target both user groups and are divided into engineered (E) and non-engineered (n-E), as shown in **Table 4A**.

2.2.6 Building Categories

The Building Category (or equivalent system of categorization) is an important classification as it defines any restrictions and limitations, as well as the level of necessary reinforcements, for different types of buildings in different types of contexts. Schools are public buildings with a higher occupancy level compared to houses and are usually rated with a higher Importance Factor (I). Contextual influences can be related to seismic zoning or local soil conditions. Therefore, stricter design rules may apply for a school building in a high seismic zone on soft soil versus a house on rock soil in a region with low seismic risk. Generally speaking, the way this Building Category is determined, if at all, is a good indication of the engineering level of the publication.

In some publications, for instance BTPMC (1999), the Building Category is related to a basic seismic coefficient, which is a combination of seismic zonation, ground conditions and building importance. The zoning data is derived from national seismic zonation maps that represent expected seismic hazard levels based on frequency and intensity of expected earthquakes in different areas. It may require interpolation of the seismic zoning factor (Z), which represents the average peak ground acceleration. Ground conditions can greatly influence the seismic behavior of a building, and the strength and stiffness of soil relates to certain values of geotechnical engineering properties, such as the soil-foundation factor (β) and the allowable bearing capacity (N_a). To obtain and interpret all this specific seismic data requires qualified engineering background. In that regard, a recommendation in the IAEE manual (Arya et al, 2014) stating that "soil investigations should be carried out to establish the appropriate allowable bearing capacity" does not align with its intended target group of non-engineers.

However, more often the Building Category is not mentioned at all, and the publication is presented as a 'one-size-fits-all' solution. If no distinction is made between higher and lower seismic levels and importance of the building, this general approach may result in excessively reinforced houses in low seismic zones, or worse, in insufficiently reinforced important buildings in an area with high seismic hazard. Or said differently, if the Building Category is not specified, it is not possible to determine suitable design rules that address the different seismic hazard levels or different building typologies. Regardless of the techniques described, such one-size-fits-all publications are deemed unsuitable for detailed design and construction purposes and have therefore been rejected from the in-depth reviews further on in this chapter.

2.2.7 Types of Non-Engineered Publications

The majority of the 47 practical manuals under review address the topic of non-engineered construction in a general way and include various chapters about different types of masonry, concrete frames, wood construction and earthen structures, such as Daldy (1972), ERRA (2007) and Arya et al (2014). This means the reader constantly has to go back-and-forth between chapters about foundations, general masonry, reinforcements and roofing, whilst filtering out the particular and relevant lines for stone masonry. This back-and-forth paging is not only time-consuming, it also increases the risk that information is misinterpreted or overlooked. In Arya et al (1980) the maximum allowed free span for stone walls was found in a footnote under a figure in the general masonry chapter. Therefore, an important question that needs to be raised is whether certain dimensions and specifications for brick masonry can be freely interchanged with applications for stone walls, and vice versa.

To underline the risk of misinterpreting or overlooking of information, the actual content that covers the topic of stone masonry was checked within the 47 practical manuals. The manuals amount to a total of 4417 pages front-to-back, which includes forewords, acknowledgments, tables of content, lists of figures, glossaries, abbreviations, appendices, reference lists etc. (18%). The remaining actual text can then be separated from background information that is irrelevant for stone, as well as chapters about different techniques like wood, earth and retrofitting (48%). The remaining chapters for masonry are then divided into relevant background information such as zoning, soil conditions and building shape (8%), masonry in general (15%), and finally into pages that are specifically dedicated to stone masonry, either in cement mortar (8%) or mud mortar (2%).

Overall, the relevant content about stone masonry within the 47 manuals is about 10%, meaning that the reader needs to go through 90% of additional text, to filter out the relevant information that is actually needed. A “Stand-Alone” (SA) stone masonry publication, or a publication that has a clearly separated chapter solely dedicated to stone masonry, will prevent any possible confusion. However, only 11 out of 47 practical manuals are marked as 'SA' in **Table 4B**.

2.2.8 Non-Engineered Seismic Codes of India and Nepal

An in-depth review of nearly 325 national seismic and masonry codes is carried out in Chapter 3. Only a handful of codes in the world exist that specifically target non-engineered seismic design, such as in Morocco for earthen structures (RPCTerre-2011, 2013) or China for construction in rural areas (JGJ 161-2008, 2008). Under certain conditions, The Iranian Seismic Code (Standard 2800, 2015) is one of very few codes that does permit buildings in rubble stone masonry (including schools), even in their highest seismic zone 1, but no practical manuals were found for the Iranian or Middle Eastern context. Since the majority of the practical design and construction manuals that were found (32 out of 47) are specifically written for the Himalayan region, it was decided to also include the Indian and Nepali codes for Non-Engineered seismic design in this review. With the introduction of code IS.13828:1993 (1993) for “Improving Earthquake Resistance of Low Strength Masonry Buildings”, India is “perhaps the first country to have developed codes on low-strength non-engineered masonry constructions” (Jain, 2000). Here, low-strength stone masonry is described as “random rubble; uncoursed, undressed or semi-dressed stone masonry in weak mortars; such as cement-sand, lime-sand and clay mud.” There is a bit of contradiction between the supposed non-engineered level of this code, as the interpretation and application of design criteria still demand rather advanced engineering skills. The latest (reconfirmed) revision IS.13828:1993 (2018) clearly defines that low-strength masonry is not permitted in building category E and “should be avoided” in category D. The code also explicitly states

that these constructions "should not be permitted" for important buildings with importance factor $I \geq 1.5$. This concludes that school buildings in low-strength masonry (two main search criteria of this literature review) are not allowed to be built anywhere in India, although the word "should" weakens these statements. For houses, no special seismic provisions are considered necessary for category B (zone II), meaning that seismic specifications only need to be applied in category C (zone III).

The Nepalese code NBC 202:2015 (2015) for "Guidelines of Loadbearing Masonry" covers rubble stone buildings in cement mortar with certain nominal reinforcements. However, all recommendations are meant for residential buildings, as NBC 202 specifies that its rules do not apply for important buildings such as schools. On the other hand, school designs that are made by qualified professionals may be approved by the local authorities. Still, in the rural and mountainous regions where rubble stone remains to be the primary construction material, both these scenarios of qualified design and required approval are highly unlikely to occur. But on a positive note, school buildings in rubble stone masonry are currently not completely ruled out in Nepal. Contrary to the previous version NBC 202:1994 (2007), the revised NBC 202:2015 makes no distinction between seismic zoning or building categories. It has become a one-size-fits-all publication which does not offer solutions that addresses different seismic hazard levels in the country.

Similar issues of practicality and readability as described for the technical manuals, such as back-and-forth paging, overlooking of information and the one-size-fits-all approach, are also noted for these national codes. They often refer to information that is printed in other codes, outside the actual publication. For example, Indian Standard IS.13828:1993 (2018) refers to IS:1904-1986 (2015) for the foundation, to IS.1893(part 1):2016 (2016) for zoning and building categories, then to IS.4326:2013 (2018) "Code of Practice" which refers to IS.1905:1987 (2017) "Unreinforced Masonry", which in turn refers to IS.1597(part1):1992 (2018) "Code of Practice for Rubble Stone Masonry". Another example is that the diameter for vertical steel reinforcements was found in a footnote under table 4, which refers to another footnote under table 3 of that code. To avoid such confusion, also for the national codes it is proposed to develop a Stand-Alone publication, which as of today does not exist anywhere in the world. As a last comment, both Indian and Nepali codes are not mandatory, but have the status of recommendations. In some areas, banks require approved designs or technical reports for obtaining a housing loan, making the codes "indirectly mandatory" at best.

2.2.9 Eligibility of Practical Manuals

Based on the definitions and search criteria as described, an eligibility check was carried out on a total of 47 relevant practical construction manuals that are published between 1972 and 2017, focusing on the following parameters:
i) Stone masonry publication
ii) For design and construction of school buildings
iii) Built in rubble stone masonry with cement mortar
iv) With nominally reinforcements added to the loadbearing system
v) According to clearly defined Building Categories
vi) Specifically targeted for Non-Engineers
vii) Preferably a Stand-Alone publication

The search criteria can be summarized as: "school buildings constructed in nominally reinforced rubble stone masonry (NRM) with cement mortar and wooden diaphragms in seismic areas."

As an additional parameter the content of stone masonry related topics was analyzed to determine to what extent all the necessary design and construction requirements are addressed, as an indication of the "technical completeness" of the publications. Following the example of Papanikolaou & Taucer (2004), who conducted a literature review on the topic of non-engineered houses in Latin-America, a point system was developed for fair comparison of 10 main topics, by dividing 78 points over 73 items (marked as xitems/xxpts). Certain items, such as main dimensions, openings and reinforcements, were given more weight in this completeness analysis, which roughly amounts to 70% for main dimensions versus 30% for construction quality related issues. The 10 main topics are as follows, of which the overall scores are included in **Table 4E**:

i) overall building dimensions, 6items/10pts
ii) foundation, 8items/7pts
iii) wall dimensions, 4items/9pts
iv) masonry and mortar, 9items/8pts
v) buttresses, 3items/5pts
vi) openings in walls, 8items/9pts
vii) horizontal reinforcements, 14items/9pts
viii) material specifications, 9items/6pts
ix) vertical steel reinforcements, 7items/7pts
x) roof construction, 5items/8pts

When combining all the above parameters, it is concluded that out of 47 publications only one manual (Desai et al, 2012) qualifies for the exact given parameters, and only one more manual has a Stand-Alone chapter for stone masonry (Arya, 2005). Both publications cover houses as well as schools, but the difference between these categories is clearly defined. Overall, only three manuals are specifically drafted for school buildings (Arya and Chandra, 1982; Arya, 1987b; Bothara et al, 2002), but in these the overall theme is brick and block masonry, with just a few additions for stone. The eligibility check shows a clear division of three groups, as presented in **Table 4**.

Group 1 includes 22 rejected manuals, of which 19 are directly excluded because the Building Category is not specified, **Table 4D**, of which 7 are post-earthquake reconstruction manuals for India and Nepal. Two manuals (Gujarat State Disaster Management Authority (GSDMA), 2001; Disaster Management and Mitigation Department (DMMD), 2007) do describe the Building Category, but apply the one-size-fits-all approach to all techniques, which is highly confusing (marked with "?"). Manuals that score lower than 50% on technical completeness, **Table 4E**, are deemed unsuitable for practical use and were also rejected from the review. Among these rejected manuals are two Stand-Alone stone publications (Murthy, 2002b; Bothara and Brzev, 2011) and one Stand-Alone reconstruction manual for post-earthquake Nepal (Pandey et al, 2017). Most unfortunate is the exclusion of Bothara et al (2002), which is specifically drafted for design of school buildings in developing countries. The Building Categories are well defined and it scores highest with 88% completeness. But unfortunately these guidelines are not for rubble stone with cement, as the manual only covers field stone with mud, bricks with mud and bricks with cement. The characteristics of group 2 and group 3 are explained in detail in the sections ahead. It is very important to note that the technical completeness is certainly no indication of the value, nor the validity of the stated information. It merely gives insight into how often and detailed the various elements are addressed in the literature, if at all. More insight about the value of the information provided about each of the sub-items is addressed in detail in the technical review for groups 2 and 3, further on.

Table 4. *Eligibility check and grouping of the practical manuals.*

Publication	Area	A. Eng. level	B. Stand-alone	C. Constr. type	D. Build. Cat.	E. Complete	Publication	Area	A. Eng. level	B. Stand-alone	C. Constr. type	D. Build. Cat.	E. Complete
Group 1: Rejected													
Daldy (1972)	gen.	n-E		gen.	-	35.3	GSDMA (2001)	Gujarat	E		H	?	70.2
Yorulmaz et al (1984)	Balkan	E		gen.	-	47.4	Murthy (2002a)	gen.	n-E		-	-	48.1
Schilderman (1990)	gen.	n-E		gen.	-	29.8	Murthy (2002b)	gen.	n-E	SA	-	-	75.6
Coburn et al (1995)	-	n-E		gen.	-	35.9	E-in-C Branch (2002)	India	E		gen.	E-A	49.4
Gov. Maharashtra (1998)	Mahar.	-		gen.	-	40.4	Desai & D. (2008)	India	n-E		-	-	81.7
Tomazevic (1999)	gen.	E		gen.	-	40.1	DUDBC (2011)	Nepal	E		H	-	38.8
Arya (2000)	-	-		-	-	17.9	Winter (2016)	Nepal	n-E		H	-	41.0
Shahzada (2007)	-	-		-	-	19.9	Ind. Railways (2017)	India	E		-	E-B	31.4
Gov. Tamil Nadu (2006)	T. Nadu	n-E		-	-	26.3	Bothara & B. (2011)	gen.	n-E	SA	gen.	-	70.5
UNDP (2007)	T. Nadu	n-E		-	-	37.5	Pandey et al (2017)	Nepal	n-E	SA	H	-	62.2
DMMD (2007)	T. Nadu	n-E		gen.	?	62.8	Bothara et al (2002)	Nepal	n-E		S!	I-III	87.8
Group 2: Houses only													
ERRA (2006a)	Pakistan	n-E		H	-	(dr)	ADPC (2005)	Nepal	n-E		H	-	76.3
ERRA (2006b)	Pakistan	n-E		H	-	75.0	DUDBC (2015)	Nepal	n-E	SA	H	-	77.0
ERRA (2007)	Pakistan	n-E		H	-	75.6	ABARI (2016)	Nepal	n-E	SA	H	-	57.1
SQCA (2010)	Bhutan	n-E	SA	H	-	(dr)	JICA (2016a)	Nepal	n-E		H	-	73.7
MWHS (2013)	Bhutan	n-E	SA	H	-	(dc)	JICA (2016b)	Nepal	n-E		H	-	(dc)
MWHS (2014)	Bhutan	n-E	SA	H	-	69.9	NRA (2017)	Nepal	E		H	-	61.9
Group 3: School Buildings													
Arya et al (1980)	gen.	n-E		gen.	I-V	60.3	BMTPC (1999)	India	E		gen.	E-B	77.6
Arya et al (1986)	gen.	n-E		gen.	I-V	(dc)	BMTPC (2000)	Uttarakh.	E		S+	E-B	67.3
IAEE (2004)	gen.	n-E		gen.	I-V	(dc)	Arya (2003)	Afghan.	E	SA	S+	E-B	73.7
Arya et al (2014)	gen.	n-E		gen.	I-V	71.2	Arya (2005)	Kashmir	n-E	SA	S+	E-D	70.5
Arya & C. (1982)	-	n-E		S!	I-V	55.1	Desai et al (2011)	Uttarakh.	n-E	SA	S+	E-D	(dr)
Arya (1987a)	Asia	n-E		S!	A-D	76.9	Desai et al (2012)	Uttarakh.	n-E	SA	S+	E-D	82.1
Arya (1987b)	-	E		gen.	-	60.6							

- \- = Not mentioned in the publication
- ? = Confusing or contradicting information
- (dr) = Draft version
- (dc) = Duplicate
- A. = Level of publication: E = Engineered; n-E = non-Engineered
- B. = Type of publication: SA = Stand-Alone stone manual or Stand-Alone stone chapter
- C. = Type of construction: H = Houses only; S! = Schools only; S+ = Specific data for schools; gen. = Buildings in general
- D. = Building Category, from highest to lowest.
- E. = Percentage of technical completeness.

2.2.10 Compatibility of Housing Designs with the Seismic Codes

Although the review of houses is not the aim of this chapter, the following brief comparison as summarized in **Table 5** gives an interesting insight into the compatibility and practical application of the non-engineered seismic codes of India and Nepal. After exclusion of drafts and duplicates, group 2 contains 8 manuals that are rejected because the Building Categories are not defined. However, these manuals have two interesting things in common. Firstly, they all are meant for Himalayan countries that still build with stone (Pakistan, Bhutan, Nepal) and secondly, they only address housing solutions (**Table 4C**).

Table 5. *House designs of group 2 compared to the Indian and Nepali seismic codes.*

Group 2. Houses in Rubble Stone Masonry	IS 13828:1993 (2008)	NBC 202:2015 (2015)	ERRA (2006b)	ERRA (2007)	MWHS (2014)	ADPC (2005)	DUDBC (2015)	ABARI (2016)	JICA (2016a)	NRA (2017)
General										
Country or Area	India	Nepal	Pakist.	Pakist.	Bhutan	Nepal	Nepal	Nepal	Nepal	Nepal
Build. Category (* = max.)	C*, B	–	–	–	–	–	–	–	–	–
Refers to code (India, Nepal)	I	N	I, N	–	I	I, N	N	N	N	N
Volume dimensions										
Build. ratio: L vs W (max.)	–	L=3W	L=3W	L=3W	L=3W	L=3W	–	–	–	L=3W
No. of storeys (max.)	2+attic	2+attic	2 sto.	1 sto.	2 sto.	3 sto.	2+attic	2 sto.	2+attic	2+attic
Wall dimensions (in m)										
Wall thickness (min. mm)	350	350	–	380	?	?	350	380	350	450
Wall thickness (max. mm)	450	–	380	–	?	–	–	450	450	–
Wall length: unsupported	5.0	4.5	7.0	4.5	?	?	4.5	7.0	4.5	4.5
Height: floor to floor (max.)	3.0	3.0	3.2	3.0	3.0	3.2	3.0	3.5	3.0	?
Walls: mortar mixture ratio	1:6 c-s	1:6 c-s	1:4 c-s	–	1:4 c-s	1:6 c-s	1:4 c-s	–	?	–
Buttress: spacing (max).	4.0	3.0	5.0	–	5.0	–	–	–	3.0	–
Openings in walls (in mm)										
Max. % total wall (1 sto.)	46%	30%	50%	50%	50%	< 1.2m	50%	50%	50%	50%
Max. % total wall (2 sto.)	37%	–	42%	–	42%	–	–	42%	42%	–
Dist. corner to door (min.)	230	1/4h(d)	600	900	1/4h(d)	?	600	1/4h(d)	1/4h(d)	1/4h(d)
Dist. corner to wind. (min.)	230	1/4h(w)	600	900	1/2h(w)	?	600	–	1/4h(w)	1/4h(w)
Piers betw. openings (min.)	450	1/2h(w)	450	600	1/2h(w)	–	600	1/2h(w)	1/2h(w)	1/2h(w)
Hor. bands for 5.0m span										
Found. beam: height (mm)	75	75-150	150	75	100	n.s.	150	305	?	–
Sill band: height (mm)	–	75	150	75	–	75	75	n.s.	?	75
Stitches	–	75	n.s.	n.s.	–	n.s.	75	n.s.	?	75
Lintel beam: height (mm)	75	75-150	150	75	100	75	150	n.s.	?	75
Top beam: height (mm)	75	75	150	75	100	75	75	–	?	75
Gable band: height (mm)	75	75	150	–	–	75	x	–	?	x
Steel bar: no. & dia. (in mm)	2ø8	2ø10,12	4ø10	2ø12	2ø12	2ø12	4ø12	?	?	–
Stirrups: dia. & c.c. (max.)	6@150	6@150	6@150	6@150	8@150	n.s.	6@150	8@125	?	–
Concrete: mix ratio c:s:a	1:2:4	M20	–	1:2:4	–	1:2:4	1:1.5:3	–	–	–
Vertical steel (dia. in mm)										
Steel diameter for 1 storey	ø10	ø12	ø12	ø16	ø12	ø10	> ø12	–	?	ø16

- = not mentioned in the publication. n.s. = mentioned but not specified
x = not allowed or advised. ? = confusing or contradicting information.

Table 5 clearly shows that i) there is hardly any agreement between both codes; ii) the manuals are not in line with the codes on almost all points, and iii) there is also lots of disagreement between the manuals themselves. This is basically the case for all main dimensions such as for lengths, heights, thicknesses, openings and reinforcements. For instance, both codes recommend a maximum free span of walls of 5.0m, whereas the manuals give values ranging from 4.5m to 7.0m. And while NBC 202 defines that houses should be built only one story high, all manuals that refer to this Nepali building code recommend heights between 2 and 3 stories.

Most striking are the differences between the ERRA (2006b) and ERRA (2007) manuals for Pakistan, both published within one year by the same organization, but seemingly compiled by two completely different teams. Also noticed are the discrepancies between the DUDBC (2015) building catalogue and the JICA (2016a) manual for house owners, which are both based on the exact same building codes and housing plans. Such differences may arise when information for general masonry is copied into stone masonry chapters, which is either incompatible, or perhaps has been altered somewhere along the line. But other than speculation about careless copy-pasting of wrong data, lack of expertise by the publisher, or overcautiousness after a disaster, no clear indication was found why the manuals deviate from the codes they refer to, and why they all publish such highly contradicting information.

2.3 Technical Review of the Practical Manuals for School Buildings

Group 3 represents the remaining 13 practical manuals that are eligible for the in-depth comparison and review of school buildings in rubble stone masonry with cement mortar. This is remarkable, as all manuals in this group refer directly or indirectly to the principles of the Indian seismic codes, while these codes prohibit the use of rubble stone masonry for school buildings in any seismic zone.

The two manuals for Educational Buildings (Arya and Chandra, 1982; Arya, 1987a) are brought back to just one, as they are almost identical. It is noted that the information in these contradicts at nearly all points with the other manual Arya published in the same year (Arya, 1987b). Further, the three manuals published by the International Association for Earthquake Engineering (Arya et al, 1986; IAEE, 2004; Arya et al, 2014) are also merged into one review, as they are nearly identical with regard to the stone masonry chapter. It means that this particular information has not changed for over 30 years since 1986. With removal of drafts and duplicates, a total of 9 practical manuals are included in the in-depth technical review.

Noteworthy is that 7 out of these 9 manuals (from now on marked as (xx/xx)), are written or co-written by Arya. He played a major role in drafting the very first manual for non-engineered construction named “Basic Concepts” (Arya, 1980), followed by the three manuals of IAEE. These are the most referred-to manuals of this review, and even the Indian code IS.13828:1993 (2018) and the Nepali code NBC202:2015 (2015) make a reference to these. Given the high influence of one author on this particular subject, and the fact that all manuals constantly refer to the same main sources over and over, it is remarkable to note that each manual presents different facts and information, as shown in **Table 6**. This overview starts with a clear lack of consensus on one of the most important parameters, being the maximum allowed Building Categories in which stone masonry is permitted (marked with *).

Table 6. *In-depth technical review for school designs according to the practical manuals of group 3.*

Group 3. Schools in Rubble Stone Masonry	Basic Concepts (Arya et al, 1980)	IAEE (Arya et al, 2014)	Educational Build. (Arya & Ch, 1982)	Masonry & Timber (Arya, 1987b)	BMTPC general (1999)	BMTPC Chamoli (Arya, 2000)	Afghanistan (Arya, 2003)	Jammu and Kashmir (Arya, 2005)	Uttarakhand (Desai et al, 2012)	Smart Shelter Found. (2007 - 2012)
General										
Country or Area	gen.	gen.	–	–	India	Uttara.	Afghan.	J & K	Uttara.	Nepal
Build. Category (* = max.)	II*- IV	I*- IV	I*- IV	–	D*- B	E*- C	E*- C	E*	E*	–
Volume dimensions										
Gen. principl. building forms	+	+	+	+	+	–	+	–	–	+
Build. ratio: L vs W (max.)	L=3W	L=3W	L=3W	–	L=3W	–	L=3W	–	–	L=3W
No. of storeys (max.)	1.5 sto	1+attic	4 sto.	1+attic	2 sto.	2+attic	2 sto.	2 sto.	2+attic	1 sto.
Foundation										
Dimensions	–	–	–	–	–	+	+	+	+	+
Mortar mixture ratio	–	–	–	–	–	–	–	–	–	1:6 c-s
Wall dimensions (in m)										
Wall thickness (min. mm)	–	300	–	–	350	–	380	–	375	–
Wall thickness (max. mm)	450	450	–	450	450	380	450	400	450	350
Wall length: unsupported	7.0	7.0	9.0	7.0	5.0	7.0	7.0	7.0	7.0	6.0
Height: floor to floor (max.)	–	3.5	–	3.5	3.0	3.0	3.2	3.2	3.2	2.6
Walls: mortar mixture ratio	1:2:9	1:4 c-s	1:4 c-s	1:6 c-s	1:6 c-s	1:4 c-s	1:4 c-s	1:4 c-s	1:4 c-s	1:6 c-s
Buttress: spacing (max).	–	3.0	–	3.0	4.0	5.0	5.0	5.0	5.0	6.0
Openings in walls (in mm)										
Width of opening (max.)	–	–	–	–	–	–	–	–	–	1200
Max. % total wall (1 sto.)	50%	30%	50%	30%	42%	50%	50%	50%	50%	50%
Max. % total wall (2 sto.)	–	n.r.	–	n.r.	33%	42%	42%	42%	42%	n.r.
Dist. corner to door (min.)	1/4h(d)	1/4h(d)	1/4h(d)	600	600	560	450	450	450	600
Dist. corner to wind. (min.)	1/2h(w)	?	1/4h(w)	600	600	560	450	450	450	600
Piers betw. openings (min.)	1/2h(w)	1/2h(w)	1/2h(w)	600	560	450	600	600	560	900
Vert. height betw. openings	1/2w(w)	–	600	–	600	–	–	–	–	n.r.
Hor. bands for 7.0m span										
Found. beam: height (mm)	75	75	75	75	75	150	?	75-100	75-100	150
Sill band: height (mm)	–	–	–	–	–	–	+	+	–	75
Stitches	+	+	+	–	–	–	–	–	+	75
Lintel beam: height (mm)	75	75	75	75	75	150	150	+	≥75	100
Top beam: height (mm)	75	75	75	75	75	150	150	+	≥75	100
Gable band: height (mm)	75	75	75	75	75	150	150	+	≥75	x
Steel bar: no.& dia. (in mm)	2⌀16	2⌀16	2⌀16	+	2⌀12	4⌀10	4⌀10	4⌀10	4⌀10	var.
Stirrups: dia. & c.c. (max.)	6@150	6@150	6@150	6@150	6@150	6@150	6@150	6@150	6@150	6@150
Concrete: mix ratio c:s:a	1:2:4	1:2:4	1:2:4	–	1:2:4	–	–	–	1:1.5:3	1:2:4
Vertical steel (dia. in mm)										
Position	–	+	+	+	+	+	+	+	+	x
Steel diameter for 1 storey	⌀12	?	⌀16-25	⌀16	⌀10	⌀12	⌀12	⌀12	⌀12	x
Protection of steel	+	+	+	+	+	+	+	+	+	x
Roof construction (wood)										
Wood dimensions	–	–	–	–	–	–	n.r.	–	+	+
Cross-bracing of trusses	–	–	+	–	+	+	n.r.	+	+	+

- = not mentioned in the publication. + = mentioned; or mentioned but not specified. n.r. = not relevant
x = not allowed or advised. ? = confusing or contradicting information.

The next paragraphs highlight some further differences and discrepancies, as well as similarities and other notable facts between the publications. As a reference for the comparison of elements, the most generally recommended unsupported wall length of 7.0m is chosen. Brief remarks are made with regard to the actually built schools in Nepal by Smart Shelter Foundation, which is included in the last column of the table. Also, some remarks are included about a set of 12 post-disaster school designs in rubble stone masonry that were made available online by the National Reconstruction Authority (NRA, 2018), of which 5 were approved by the Ministry of Education in Nepal. (However, a check in 2021 revealed that these designs are no longer available on that website).

2.3.1 Overall Building Dimensions

The maximum ratio of width versus length for the overall dimension of the building volume is only mentioned in (25/47) but the majority (20/25) agrees on L=3W, although L=2W, L=4W and even L=3.5W were spotted as well. There is no consensus in group 3 on the maximum height of the building, where five different options are noted; 1+attic, 1.5 story, 2 stories, 2+attic, and 4 stories.

Most manuals include some guidance on site considerations (31/47) and on building shapes (33/47). Separation between building volumes by creating a gap is explained in (25/47) but varies from 1.5-15cm. Detailed building plans however are seldom found. Illustrations are generally limited to one-box-type examples (such as **Figure 6**) to explain mechanisms or to point out elements. The JICA (2016a) housing manual and DUDBC (2015) building catalogue have very nicely detailed illustrations and isometric views of houses, but nothing similar was found for schools.

2.3.2 Foundation

The least covered and most incomplete topic of all, the foundation is not even mentioned in (20/47). Only (4/9) in group 3 have included some general information about width, depth and shape, and/or have specified this for different soil types. But not one manual makes any distinction for multi-story buildings, mentions application and function of a firm layer in the bottom, has defined the minimum height above ground level, or mentions anything about drainage around the building. Waterproofing or a damp-proof course (DPC) on top of the foundation is mentioned in (5/47), but none specifies exactly how to apply this.

Most surprisingly, no mortar specifications for the foundation are given at all in group 3, and neither in (37/47) overall. Within the remaining (10/47) some recommend mud mortar below ground level, where others specifically prohibit mud.

2.3.3 Wall Dimensions and Specifications

There is no consensus on the wall thickness, with a minimum ranging from 300-380mm and a maximum from 380-450mm. The maximum free span highly varies between 4.5-9.0m, although the consensus is 7.0m (7/9). However, it is seldom clear what exactly is defined: the distance between the interior sides of two cross-walls, or the center-to-center dimension. The maximum wall heights in group 3 vary between 3.0m, 3.2m and 3.5m, but also here it is seldom clarified from exactly where to where this is measured; free interior height or center-to-center of floors.

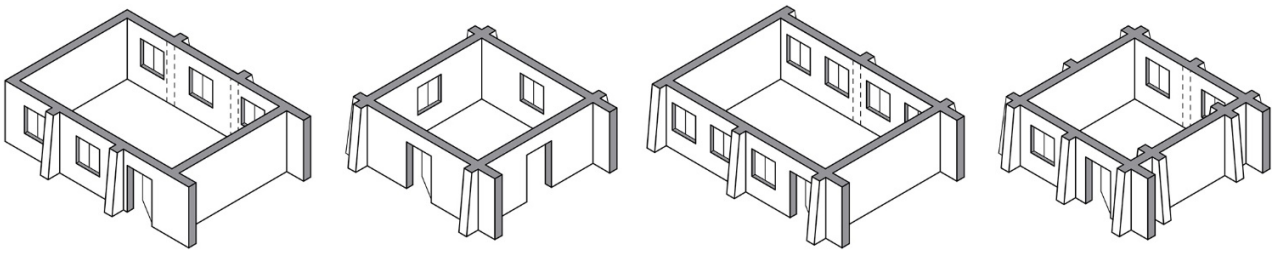
Many varieties are specified for the mortar of the rubble stone masonry, such as cement-sand mortars, lime-based mortars and even mud, whereas group 3 is divided between 1:4 or 1:6 cement-sand mixtures. ADPC (2005) notes that “the thickness of mortar plays a vital role in the strength of masonry

and should be optimum. Thin mortars cannot bond the units properly, and thick mortar makes the wall weaker". However, the thickness of the joints is only mentioned in (4/47), ranging from 8-25mm. Only (3/47) manuals specify that freshly mixed mortar must be used within 25 minutes to one hour. Plastering of walls is also seldom mentioned (7/47).

Almost all manuals include items related to construction quality, such as how to lay the stones in coursed and level layers of 60cm lift, or how to place and overlap them in corners and sections. Few manuals warn against use of round boulders, and just some specify stone dimensions, such as 450x275x150mm in MWHS, 2014. Most recommended is the use of bond stones in a staggering pattern of 1.2m horizontally and 0.6m vertically (37/47).

2.3.4 Buttresses

Only (27/47) have included information about buttresses. Both Indian and Nepali non-engineered codes mention that buttresses are required, but only when the maximum allowed free wall span is exceeded. Both codes locate these at intermediate points, but with different dimensions of the intervals (**Figure 6A**). The previous Nepali code NBC202:1994 (2007) however showed buttresses at all wall ends of corners and T-sections (**Figure 6B**), which was contradicted by another illustration of a "correctly buttressed single-story school-building", with buttresses only at the short walls (**Figure 6C**). It seems that somehow the previous recommendations have been mixed up with the revised code recommendations, as noticed in the examples that were published online by NRA, 2018 after the 2015 earthquake in Nepal (**Figure 6D**). Further, not one manual explains how to place stones into the buttresses to create good bonding with the wall, nor describes the effect of placing openings directly next to buttresses, as in **Figures 6A, 6C** and **6D**.



(A) **(B)** **(C)** **(D)**

Figure 6. *Principles of **(A)** intermediate buttresses (following Desai et al, 2012). **(B)** buttresses at all ends of walls (following NBC202:1994). **(C)** buttresses only at ends of short walls (following NBC202:1994). **(D)** buttresses at all ends of walls and at intermediate points (following NRA, 2018). (all by courtesy of SSF).*

2.3.5 Openings in Walls

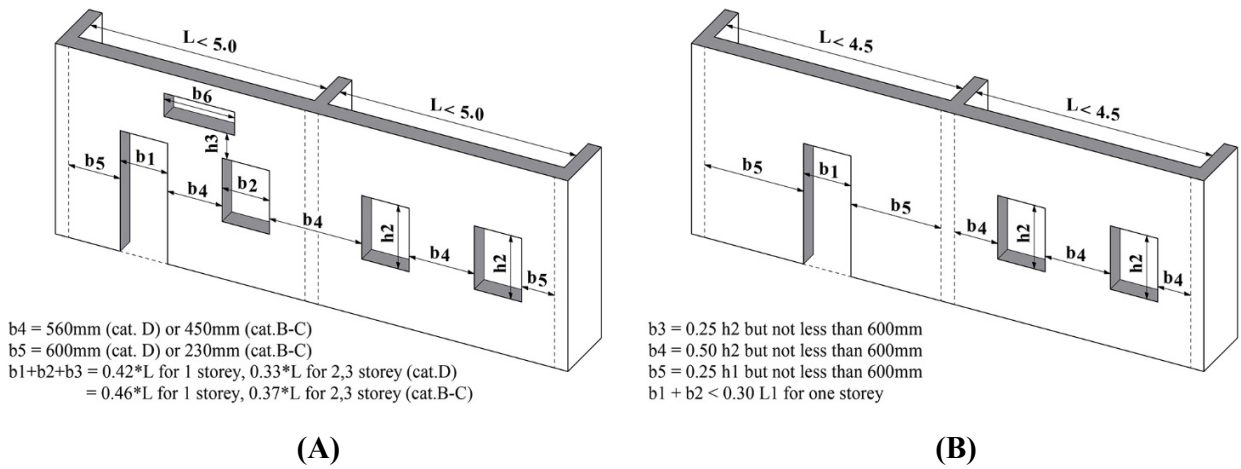
This section explains different methods to determine the maximum dimensions of openings in a wall, and the implications when these maximum values are exceeded.

2.3.5.1 Maximum Dimensions of Openings

Arya et al (2014) explains that "openings tend to weaken the walls, and the fewer the openings, the less the damage suffered during an earthquake". Therefore, a maximum percentage is determined for the total length of openings, divided by the total length of the wall panel. For single-story buildings the

group 3 manuals (6/9) define different values of 30%, 42% and 50%, whereas for more stories these values decrease. It must be noted that maximum 30% of opening length is very limited. If we follow NBC202:2015 (2015) with maximum free span of 4.5m, this means that just one opening of 1.35m per side of the room is possible. To install two smaller openings of 0.70m width is not likely, as also the thickness of the wooden frame must be deducted, with the result that insufficient daylight will enter the room. Door openings must certainly be wider than that. Further, NBC 202 has only included the requirements for one-story buildings, whereas for brick masonry a distinction is made for different floor levels.

Another approach is to define minimum dimensions for wall lengths, needed for the following 5 situations: i) from corner to door, ii) corner to window, iii) pier between door and window, iv) pier between two windows, and v) vertical height between two openings. Some manuals specify fixed values ranging between 230-900mm, whereas others calculate the wall length as a quart or half of the adjoining opening height. In some cases, the measurements are taken from the insides between the cross-walls, in others from center-to-center of walls, or even from the outside corner of the building. Clearly the Indian codes (**Figure 7A**) and Nepali codes (**Figure 7B**) show a different approach for the wall dimensions around the interior walls. The reader must also pay attention to the different types of notation, such as > or ≥ or ≧ or ≯. Overall, it results in numerous variations without any consensus or consistency whatsoever.



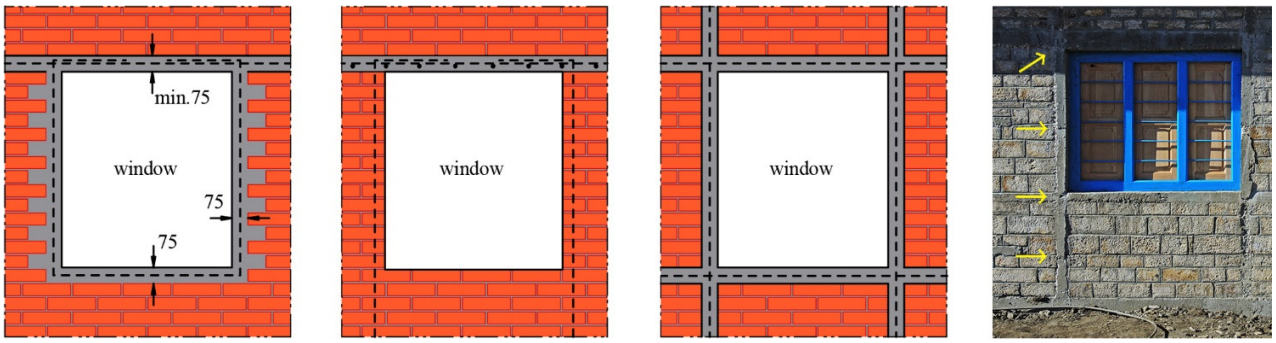
(A) **(B)**

Figure 7. *Principles of dimensions of openings according to* ***(A)*** *Indian seismic codes (following IS.13828:1993) and* ***(B)*** *Nepali seismic codes (following NBC202:2015). (both by courtesy of Smart Shelter Foundation).*

2.3.5.2 Boxing of Openings

Both Indian and Nepali codes dictate "boxing of openings", but only when the opening size exceeds the allowed dimensions. For such case, IS.13828:1993 (2018) describes that openings "should be strengthened by providing reinforced concrete lining with 2 high strength deformed (HSD) bars of 8mm dia.", but without any mention or specification for the stirrups. According to Arya (2000) such frames "will not be as effective in aiding the shear wall action unless properly connected to the walls through shear keys". In total (19/47) have included a variation of **Figure 8A**, but this concept of boxing is meant for brick masonry. Not one manual describes in detail how to execute this for rubble stone masonry, such as masonry pattern and interlocking of stones.

NBC202:1994 (2007) showed an older alternative detail, **Figure 8B**, in case "the vertical opening of the wall is more than 50% of the wall height". This rule certainly applies to all doors, as they literally divide a wall into two portions, but only (1/47) followed this advice. The figure shows vertical bars that must be installed in the jambs, but without any steel specifications or further detailing. This solution, which will be difficult to execute properly, has been replaced by the latest trend, which is to include concrete posts next to windows, all the way from the top beam to the foundation beam (**Figure 8C**), as also noted in 6 of the 12 school designs published by NRA (2018). However, the need for this is not described in any code or manual. **Figure 8D** show such example, which is built without sill beam and without the tooth connection. The builders told that it created all kinds of practical issues, such as accumulation of debris falling into the gap, and that proper casting was only possible in lifts of 60cm. This creates interruptions in the posts, which likely results in insufficient strength of these elements. Further, recent testing on confined masonry panels by Singhal and Rai (2017) show that a continuous sill beam under an opening behaves much better than continuous vertical posts next to openings. This should be verified for nominally reinforced stone masonry as well.



(A) **(B)** **(C)** **(D)**

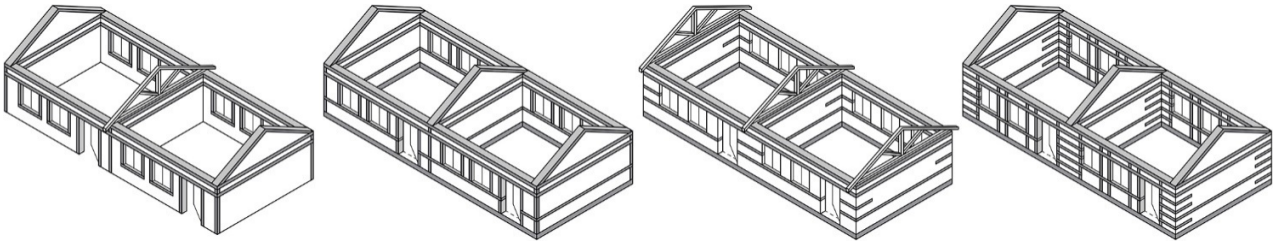
Figure 8. *Principles of boxing of openings with* ***(A)*** *concrete frames with shear keys (following IS 13828:1993).* ***(B)*** *vertical bars (following NBC 202:1994).* ***(C)*** *continuous vertical posts and horizontal beams (following NRA, 2018).* ***(D)*** *Practical example of vertical posts next to openings. (A-C by courtesy of Smart Shelter Foundation, D by courtesy of Preci).*

2.3.6 Horizontal Reinforcements

The Nepali code NBC202:2015 (2015) states that "the most important horizontal reinforcing is by means of reinforced concrete bands provided continuously through all load-bearing longitudinal and transverse walls, at plinth, lintel and roof-eave levels, and also at the top of gables." This section is focusing on beams of reinforced concrete (whereas thinner members with a lesser height are often referred to as bands), although alternatives can be made of wood, steel and bamboo.

The importance of horizontal reinforcements is not disputed by any of the codes or publications, but their positions and dimensions certainly are. **Figure 9** shows the evolution of different principles over the years. The majority of publications follow the recommendations of the Indian codes, such as Arya (2000); Arya et al (2014) and include only the lintel and top beam (**Figure 9A**). Gradually over time, some manuals start to add more reinforcements such as the plinth beam, sill band (**Figure 9B**) and stitches (**Figure 9C**). Nepal has revised the concept of minimum 2 beams in the previous code NBC 202:1994 (2007) to horizontal bands at 5 to 6 levels (plinth, sill, lintel, top and stitches at two levels

depending on height intervals) in NBC202:2015 (2015). Therefore, it is surprising to see that many designs after the 2015 Nepali earthquakes incorporate reinforcements at 6 or even 7 levels (as published online by NRA, 2018), sometimes at intervals of less than 300mm in height, for which no logic or explanation was found (**Figure 9D**).



(A) **(B)** **(C)** **(D)**

Figure 9. *Principles and evolution of adding horizontal bands with* ***(A)*** *2 beams and gable band (following Arya, 1987a).* ***(B)*** *4 beams and gable band (following ERRA, 2006b).* ***(C)*** *total 5 beams & stitches (following Schildkamp, 2015a).* ***(D)*** *total 7 beams & stitches, plus gable band and full vertical posts next to openings (following examples as published online by NRA, 2018) (all by courtesy of Smart Shelter Foundation).*

2.3.6.1 Lintel Beam and Top Beam

The lintel beam is generally seen as the most important beam of all (9/9), which continuously runs directly over all openings. Together with the top band, also known as floor, eave or roof band, these beams add the most to the box-action of the building, by preventing separation of wall connections and out-of-plane failure of the walls. If the floor height is limited, meaning there is only a thin layer of spandrel masonry on top of the lintel, some manuals recommend combining lintel and top beam into one. Arya et al (2014) specifically mentions this for walls with less than 2.5m floor-to-floor height.

2.3.6.2 Sill Band and Stitches

There is not much agreement about the need for the sill band under the windows and/or stitches in corners and T-sections. The sill band is only recommended for the highest Building Category and in just (2/9), but both for different reasons; Arya (2003) demands it only for 2 to 3 story buildings and Arya (2005) for buildings with a high Importance factor. The main critique on the sill band is that it is not continuous due to disruption of door openings, although ERRA (2007) states that it is "best to provide continuous sill band also", which simply is impossible. It is interesting to note that a thorough inspection of all 15 SSF school projects (either in stone or block masonry) after the 2015 earthquakes, revealed only some minor hairline cracks in 8 schools, right between the sill beam and the masonry on top of it. This is likely caused by slight rocking of heavy masonry piers, which may be avoided by inserting dowels between the bands and the masonry. The fact that the damage was insignificantly minor also suggests that the horizontal reinforcements played an important role to avoid shear cracking in the piers and spandrel masonry, but all these assumptions need further in-depth validation. Stitches are mentioned in (5/9) and many alternatives are given such as concrete bands, wooden ladders and steel dowels or metallic mesh in horizontal joints. Desai et al (2012) describes stitches only for the highest seismic zones, and Arya and Chandra (1982) recommends stitches at every 40cm lift. Arya (1987a) explains that dowels can be used as an alternative for the lintel in the lower seismic zones at 60cm intervals throughout the height of the wall, and in the higher zones stitches can be added at sill level in addition to the lintel beam.

2.3.6.3 Gable Band

The gable band is mentioned in all (9/9) of group 3, in case a masonry gable is built. Some manuals place stone gables only on the end walls (**Figure 9A**) and others on the cross walls as well (**Figure 9B**). However, the more recent manuals such as Desai et al (2012); NRA (2017) recommend a fully trussed roof with light wooden gables, as heavy masonry gables, even with gable band, still have the risk of toppling during an earthquake. The roofs of Smart Shelter Foundation are also built this way (**Figure 9C**).

2.3.6.4 Dimensions of Concrete Beams and Steel Reinforcements

All (9/9) agree that the beam dimensions and their required steel reinforcement depends on room span, importance of the building and number of stories. But at the same time all manuals follow a general one-size-fits-all approach, similar to IS.13828:1993 (2018) which recommends minimum 75mm thickness of beams with 2ø8mm steel rods, regardless of floor span or type of beam.

Firstly, the manuals make no difference between the type of masonry, for instance Arya et al (2014) states that "all the horizontal reinforcing recommended for brick buildings, may be used for random rubble constructions as well." As the width of brick walls is generally around 100-230mm versus 350-450mm for stone walls, the question is whether these values and dimensions can indeed be freely interchanged. Secondly, all (9/9) define just one thickness and apply it for each beam, band or stitch. However, no consistency or consensus is found for this thickness, and neither for the numbers and diameters of the steel reinforcements. Recommendations range from bands of 75mm thickness with 2ø10mm or 2ø16mm steel bars, to beams of 150mm thickness with 4ø10mm (**Table 6**), to even a foundation beam of 305x430mm with 4ø12 bars (ABARI, 2016). Only (1/47) suggests placing an extra third horizontal bar over openings in the lintel beam (Bothara et al, 2002). Dimensions of the stirrups are mentioned in (32/47), generally set at 6mm steel bars with 150mm center-to-center interval (21/32), with deviations of 4-10mm diameter rods with 200-370mm spacing.

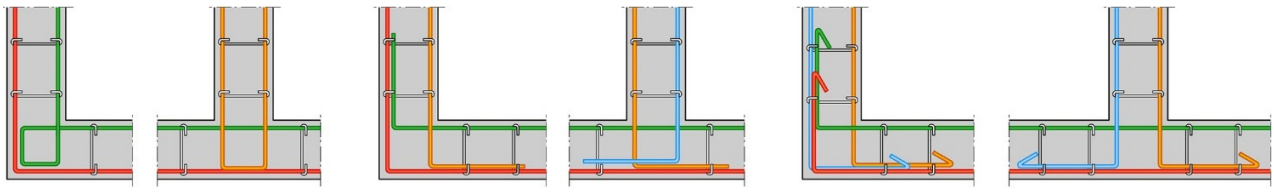
2.3.6.5 Detailing of Horizontal Reinforcements

Most manuals include details for bending of steel bars in corners and T-sections, for which three different options are found, **Figure 10**. Overall, no indication was for which one behaves better or worse during a seismic event. Some of these patterns will be difficult to bend with thick steel diameters of ø16mm or even ø20mm (UNDP, 2007). The splicing length is mentioned only in (13/47), ranging between 400-750mm, or specified as lengths of minimum 40d, 50d and 60d. However, (6/13) including Arya et al (1980) clearly mention that splicing is not allowed in corners, which goes against **Figure 10C**. The length of the steel hooks for stirrups is generally set at 60mm (18/47), but not one manual mentions whether these hooks should be applied in an alternating pattern, as often seen in publications about reinforced concrete.

Steel qualities are only specified in (16/47). Arya et al (2014) writes in a footnote: "Bar diameters are for mild-steel. For high strength deformed bars, equivalent diameter may be used", but these then must be found from external sources. The steel quality for stirrups is specified only (/47) times, being mild or plain steel (4/7), high-strength deformed steel (1/47) or specifically "no plain steel" (2/47). Not one manual explains the difference between using plain or deformed steel for stirrups. More importantly, the ratio of the concrete mix is not mentioned in almost half the publications (22/47), and the remaining half offers two different options, being 1:1.5:3 or 1:2:4 of cement : sand : aggregates. Some manuals

specify the mixes as M15 and M20 or mention that the concrete must have a minimum strength of 15 MPa after 28 days curing, but such specifications may not be understood by the non-engineered target groups. The maximum size of aggregates is defined in only (7/47) and results in 6 different sizes, which are 10, 12, 18, 20, 25 and 30mm.

The minimum concrete cover on steel bars is specified in (27/47), ranging from 20-30mm, whereas most examples show a distance from center of steel bar to the outside of beam. If we take 30mm cover and we have bars of 12mm and stirrups of 6mm, this results in a concrete layer of just 18mm at all stirrups, which seems insufficient. Further, only (6/47) mention the importance of keying, by means of sticking pieces of steel or stone into the wall before casting a beam, in order to improve bonding between masonry and concrete beam or band. And only (5/47) include information about the procedures of mixing, watering and curing to obtain good quality concrete.



(A) **(B)** **(C)**

Figure 10. *Principles of different steel reinforcement patters in beams, following the recommendations made in* ***(A)*** *Arya et al (1980),* ***(B)*** *UNDP (2007),* ***(C)*** *Arya et al (2014). (all by courtesy of Smart Shelter Foundation).*

2.3.7 Vertical Reinforcements

A heavily debated topic is the need of incorporating vertical reinforcements in the walls. Smart Shelter Foundation left these out for two reasons. Firstly, it is questioned whether a relatively small number of steel rods will provide sufficient ductility in such thick walls. And secondly, a vertical disruption in the critical connections may weaken, rather than strengthen these.

Clearly, the practical manuals are in favor (35/47) of inserting them, whereas (31/35) prefer steel bars, (1/35) wooden or bamboo poles, and (3/35) have not defined the material. Of the remaining (12/47) none explicitly prohibits the vertical reinforcements, but it is unclear whether this is done intentionally, or if the topic is simply overlooked. The most recommended locations of steel bars are in the corners (27/31), T-sections (25/31) and next to openings (25/31), although boxing is often preferred when dimensions of openings are exceeded. However, not one manual has defined the need and maximum spacing of vertical reinforcements in cross-walls, which often have no openings at all. In some manuals steel bars are inserted inside the buttresses (5/31).

There is no consensus on the steel diameter, with diameters ranging from 10, 12 to 16-25mm, whereas (20/31) describe different diameters in walls of multi-story buildings. Start and end detailing of the bars is seldom described (9/31) and there is no clear verdict whether bars start in the bottom of the foundation or in the plinth beam, and if they end in the lintel or in the top beam. The bending length for anchoring is either 450mm, 55d or 60d, and splicing of the steel for multiple stories (3/31) is defined as 600mm, 50d or 60d. Only (1/31) suggests that the bars must be tied to the horizontal reinforcement of the concrete bands (Desai et al, 2012).

In (25/31) it is described how to protect the steel against corrosion, by casting a concrete core around the vertical bar, following the principle of **Figure 11A**. This detail is often printed together with **Figure 11B** that shows the position of a through stone in the T-section, such as in IS.13828:1993 (2018); NBC202:2015 (2015); IAEE (2004); Arya et al (2014). It must be stressed that this solution is simply not possible, as wherever a bond stone is located, there simply cannot be a vertical bar, and vice versa. However, this contradiction has not been rectified for over 30 years in these main publications, since it was first published in Arya et al (1986). Some manuals however did spot this discrepancy and have published the principle of **Figure 11C**, where trough stones are placed next to the vertical steel bar. These describe a concrete core of 75-100mm and through stones of 150mm thickness, but this means that detailing of through stones all around the steel bar will not fit in a wall of 350mm thick. Not one manual has fully detailed these masonry patterns for the corners, T-sections, jambs of openings or the buttresses.

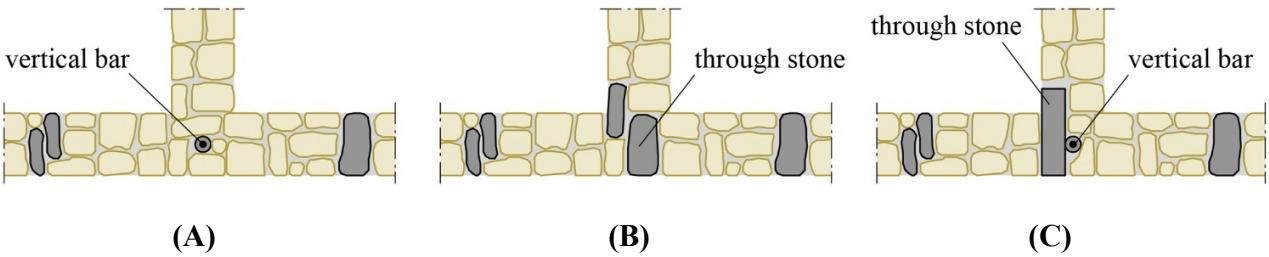


Figure 11. *Principles of masonry details with* ***(A)*** *vertical steel bar in T-section and* ***(B)*** *through stone in T-section (both following Arya et al, 2014).* ***(C)*** *vertical steel bar and through stone in T-section (following BMTPC, 2000). (all by courtesy of Smart Shelter Foundation).*

2.3.8 Roof Structure

The roof structure plays an important role in the box-like behavior of a building. But together with the foundation this is the least covered and most incomplete topic, where (18/47) do not mention anything at all, (2/47) only address flat earthen roofs, and (14/47) have included one single line, either that "the roof needs to be as light as possible", or that "the roof must be properly anchored to the walls". Bracing in the roof planes is recommended in (8/47), cross-bracing in-between the wooden trusses only in (1/47) (ERRA, 2007) and installing of a stiff ceiling in (4/47). Detailing and specification of wood dimensions is defined in just (4/47).

2.4 Conclusion

A literature review of 47 relevant field manuals and 2 "non-engineered" seismic codes was carried out, for the specific search criteria of "school buildings constructed in nominally reinforced rubble stone masonry (NRM) with cement mortar and wooden diaphragms in seismic areas." The following was observed and concluded:

- With regard to stone masonry in the Himalayan region, and with India and Nepal being the main focus of this review, the codes of these countries only allow stone masonry for buildings with importance factor 1.0. As school buildings have an importance factor of 1.5, this means these codes prohibit the use of stone masonry for construction of schools in any seismic zone, although there is some room for interpretation in the wording of the clauses. It is however remarkable that several manuals exist that are based on these codes, but still address and allow the design of school buildings in rubble stone masonry in highly seismic areas. This includes the Nepali Government which had approved several designs for school buildings in rubble stone masonry.

- Based on the above-mentioned search criteria, added with an assessment of completeness and relevance, 22 manuals were rejected and 12 manuals were found that address solely the design rules for houses. These are all from Pakistan, Bhutan and Nepal, and were briefly compared with the Indian code IS.13828:1993 (2018) and the Nepali code NBC202:2015 (2015). Only 9 manuals (of which 7 are co-written by Prof. Arya) were eligible for an in-depth review of school buildings, even though this conflicts with the regulations of the current seismic building codes.

- It is noticed that most information comes from just a few main sources, being "Basic Concepts" (Arya et al, 1980), "Educational Buildings" (Arya and Chandra, 1982) and "Guidelines for Earthquake Resistant Non-Engineered Construction" (Arya et al, 1986). No reasons were found why this information gets altered along the way. The same illustrations and tables are copied repeatedly, including apparent conflicts between the details, as seen for vertical steel and through stones. The fact that such contradictions have not been rectified in the latest versions, such as Arya et al (2014), as well as the fact that key documents such the Indian code IS.13828:1993 (2018) have never been properly updated, are indications that the knowledge has not evolved or progressed much since the 1980s.

- The conclusion for both reviews of houses (even though not the aim of this chapter) and schools is the same: Among these manuals, no consistency nor consensus was found for any of the design or construction related features for almost all key topics, such as main dimensions, openings and reinforcing elements.

- Ironically, all the above brings us to the same conclusion made by Arya at the 1977 World Conference on Earthquake Engineering in New Delhi (Arya, 1977), which ultimately led to the development of the first publication for non-engineered construction in 1980. He states that "A review of the earthquake codes of various countries shows that much of the information is empirically based and not theoretically derived. In that respect the recommendations must be subject to continuous review and change as more data becomes available."

Looking at the current state of the available information, Arya's statement of 1977 still seems valid today, and the author of this thesis finds this situation no longer acceptable. The findings of this chapter will be extended with a worldwide review of national seismic and masonry codes in Chapter 3.

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Chapter 3

Rubble Stone Masonry Buildings with Cement Mortar: Design Specifications in Seismic and Masonry Codes Worldwide

Summary

Nearly 325 national seismic and masonry codes from all over the world have been analyzed, of countries where stone masonry was, or still is, abundantly practiced. This chapter compares and summarizes design specifications and construction requirements for both houses and schools, with a specific focus on "nominally reinforced rubble stone masonry (NRM) with cement mortar and wooden diaphragms in seismic areas". Currently, the technique is only allowed and described in some detail in the seven codes of Nepal, India, China, Tajikistan, Georgia, Iran and Croatia.

It is concluded that the design specifications vary greatly without any consensus on the main sizes, dimensions or details. This raises questions about the completeness and correctness, as well as the reliability and actual value of the knowledge in this field. It is further observed that types of stone masonry and stone properties are seldom clearly described in the codes. It is also noted that several countries where stone masonry is still broadly practiced, are currently not allowing the technique (or have no codes in place), such as Afghanistan, Pakistan, Bhutan, Azerbaijan, Kyrgyzstan, Morocco, Tunisia, Turkey, Yemen and Albania. This, however, does not serve the current engineering practices and construction needs in these countries.

To address all shortcomings, the chapter recommends clear descriptions and terminology; the international adaption of NRM as a fourth masonry category; and the development of a stand-alone code specifically for this technique. This envisions a full assessment, validation, optimization and complementation of the existing knowledge, by means of the current state-of-the-art for calculating, testing and modeling. The findings of this chapter will serve as the starting point for the upcoming chapter, which will complement the seismic demand with hand-made base shear calculations for countries that still allow the technique.

3.1 Introduction

The previous chapter concludes that with regard to "non-engineered seismic principles" of rubble stone masonry buildings, no consistency nor consensus was found in the available technical design and field construction manuals, for any of the design or construction related key features and reinforcing elements. The objective of this chapter is to analyze and compare current practices of rubble stone masonry buildings with the design specifications and construction requirements, as dictated by national seismic and masonry codes. The focus is on newly constructed houses and schools, for which the specific search criteria are similar to the previous chapter: "low-rise buildings with cement-mortared rubble stone masonry walls, that are brought to courses and nominally reinforced with reinforced concrete bands, with wooden floors and a wood-trussed roof" (**Figure 5** and **Figure 12**). To avoid confusion with "Unreinforced Masonry (URM) that needs certain additional reinforcements" in seismically active areas, the previous chapter proposes the introduction of a fourth type of masonry (as well as the international adoption) of the term "Nominally Reinforced Masonry" (NRM).

Figure 12. *Nominally reinforced random rubble stone masonry with cement mortar and brought to courses (by courtesy of Smart Shelter Foundation).*

The review in this chapter is not limited to the Himalayan region but is extended worldwide and includes all countries where stone masonry is still practiced today (whether it is allowed or not by their codes), as well as countries that had a rich culture of stone masonry in the past and which potentially could (or should) reintroduce the technique. Nearly 325 seismic and masonry codes of countries worldwide have been analyzed, divided over five continents and into different time frames going back as far as the 19th century. The focus is on those countries where the technique is still being utilized, as well as on countries where it potentially could be used (again). Countries are grouped by region such as the Himalayas, Central Asia, the Caucasus, the Middle East, Northern Africa, and parts of East and South Europe. The review aims to trace when and where certain rules came into existence, how they have changed over time, and if there are similarities between codes and countries.

Several countries that possess a high seismic risk have been excluded from the review since these never had a past history nor have a present culture of stone masonry, such as Japan, Taiwan, Indonesia, the Philippines, USA, Canada and New Zealand. For the same reason, all South and Central American countries that have significant seismic hazard are excluded as well. Here the main construction practices for low-rise and low-cost housing consist of natural materials such as bamboo and earth (adobe, rammed earth, wattle-and-daub), or Confined Masonry with bricks or concrete blocks. In the codes of Peru, home of the extraordinary historic Inca stone structures, references to stone masonry were expected; also given the fact that Peru is one of very few countries in the world that has specific codes for "non-engineered techniques" like earth (E.080, 2017) and bamboo (E.100, 2012). But other than a few minor remarks about using stones in foundations and civic works, nothing for rubble stone masonry is described in any of the national codes of Argentina, Chile, Peru, Ecuador, Colombia, Venezuela, Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, Mexico, Dominican Republic, Haiti and Cuba. A plausible reason is summarized by one line in the seismic code of Costa Rica: "Historical constructions and monuments that have a cultural or historical value, many times are built with materials that are not commonly used today, such as adobe, bahareque and stone" (CSCR2010, 2014).

This worldwide review describes the historic background and analyzes the current possibilities and limitations of rubble stone masonry, following the search criteria as described in the previous chapter. It compares the main design requirements, such as overall length, width and height dimensions of the buildings; minimum and/or maximum thickness and dimensions of walls elements and openings; and specifications of main horizontal and vertical reinforcements. It is important to note that all codes are read and analyzed in their original languages by at least one (and preferably two) native speaking experts from each country; all mentioned in the acknowledgments. Except for China, most Himalayan codes are primarily published in English, but this is not the case for almost all other countries. Furthermore, the codes are followed as literally as possible, aiming to avoid opinion and interpretation. Such extensive and complete overview with regard to rubble stone masonry in seismic areas has not been presented before.

A final table summarizes all design requirements as dictated by the national codes in which stone masonry is currently still allowed. Based on these specifications, two case study buildings will be developed and presented for further detailed seismic analysis and calculations in the next chapter that compares the code dictated base shear seismic demand.

3.2 Rubble Stone Masonry in the Himalayan Region

The Alpine-Himalayan belt is one of the most earthquake-prone regions in the world, caused by movement of the Indian Plate toward the Eurasian Plate with a rate of approximately 35-50mm between western to eastern plate boundaries (Jade et al, 2017). Rubble stone masonry remains to be a primary construction method in this region and the review of the Himalayas includes Nepal, India, Pakistan and China. Afghanistan is often regarded as part of Central Asia, but since they follow US-based rather than Russian-based codes, the country is included here. The kingdom of Bhutan, where stone masonry is still abundantly in use, does not have a seismic or masonry code of its own and refers to the Indian codes (Thinley et al, 2017). Stone masonry is only discussed in its Bhutanese Architecture Guidelines (Royal Government of Bhutan, 2014), which focuses solely on aesthetic features of buildings such as building shape, roof form and window ornamentation, without any consideration for structural stability of the building. Bangladesh, although bordering the Northeastern Indian states where stone masonry is broadly practiced, does not have a culture of stone masonry and the technique is not mentioned in their building code (BNBC-2017, 2017). The countries east of the Himalayas bordering China and extending further into Southeast Asia either have a low seismic risk, or rubble stone is not a common material for buildings, such as Myanmar, Laos, Thailand and Vietnam. **Figure 13** shows the main mountain ranges in the South and Central Asian regions.

3.2.1 Nepal

The first set of Nepal's National Building Codes (NBC) was published in 1994 after the 1988 Udayapur earthquake in Eastern Nepal. The first seismic code NBC 105:1994 (2007) divided the country into three seismic risk zones: A - widespread damage and collapse; B - moderate damage; and C - minor damage, but it did not address different techniques or materials. Regarding stone masonry, the codes of interest were NBC 202:1994 (2007) "Mandatory Rules of Thumb for Loadbearing Masonry" and NBC 203:1994 (2007) "Guidelines for Earthquake-Resistant Construction of Low-Strength Masonry", but the information was perceived as highly contradicting and confusing (Schildkamp and Araki,

2019a). The first revisions in 20 years, although completed just before the devastating Gorkha earthquakes in 2015, were made available to the public 4 years later; in June 2019. Here the techniques of stone masonry with cement mortar (NBC 202:2015, 2015) and mud mortar (NBC 203:2015, 2015) are more clearly divided. The objective of NBC 202 is "to introduce earthquake-resistant features to non-engineered buildings during their construction (…) to achieve an appropriate level of earthquake resistance in non-engineered load bearing masonry buildings constructed in Nepal. (…) it does not render masonry buildings able to totally withstand any earthquake without any appreciable damage, however it is intended to limit the damage to a level which does not threaten human lives and which can be repaired quickly." The code covers rubble stone buildings in cement mortar with a maximum height of 2 stories plus attic (although not recommended on soft soil), a free wall span of 4.5m and a maximum room area of 13.5m^2. It describes a maximum floor-to-floor height of 3.0m, minimum wall thickness 0.35m, and minimum masonry width in corners, as well as for piers, of 600mm. It further recommends replacing heavy masonry gables with a light wooden alternative. Horizontal bands and reinforcements must be included at 6 levels (plinth, sill, lintel, top and stitches at two levels), and vertical bars at all critical wall connections and jambs of openings. Mortar shall not be leaner than 1:6 cement-sand ratio with a minimum compression strength of 3.0 N/mm^2 at 28 days, according to the (unrevised) code NBC 109:1994 (2007) "Masonry Unreinforced".

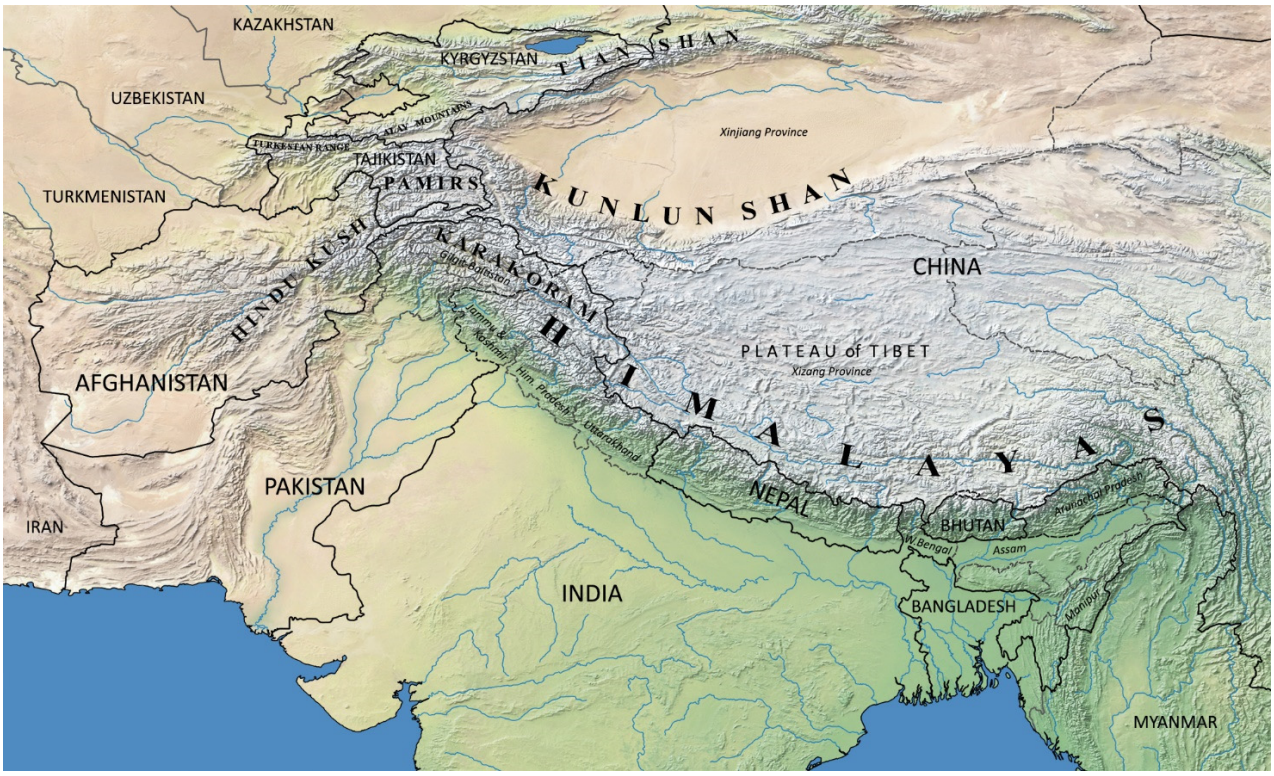

Figure 13. *Main mountain ranges of the South and Central Asian regions (original source: Natural Earth raster + vector map).*

All these recommendations are meant for residential buildings, as NBC 202 specifies that its rules do not apply for important buildings such as schools. However, school designs that are made by qualified professionals may be approved by the local authorities, of which examples were published online by Nepal Reconstruction Authority (NRA, 2018). Still, in the rural and mountainous regions where rubble stone remains to be the primary construction material, both these scenarios of qualified design and required approval are highly unlikely to occur. But on a positive note, school buildings in rubble stone masonry are currently not completely ruled out in Nepal. This includes even the highest seismic zone with a mapped Peak Ground Acceleration (PGA) of around 0.4g, as outlined on the new seismic hazard map in the draft version of the updated (and about to be published) seismic code NBC 105:2020 (2020).

Contrary to the 1994 set, the revised NBC 202:2015 makes no distinction between seismic zoning or building categories. It has become a one-size-fits-all publication which does not offer solutions that addresses different seismic hazard levels in the country. It is further noted that both codes (NBC 202 and 203) are nearly identical regarding the main dimensions, such as building height, openings and reinforcements. NBC 203 for mud mortar is actually more generous by allowing a maximum free wall span of 12 times the wall thickness (12x0.45=5.4m) versus 4.5m in cement mortar, which seems peculiar. Both codes have a disclaimer on the cover page, stating that "the publication represents a standard of good practice and therefore takes the form of recommendations. Compliance with it does not confer immunity from relevant legal requirements, including bylaws." This makes them indirectly mandatory, but if and how this is enforced, especially in rural areas, is unclear.

3.2.2 India

The Indian Standard IS:1893 is the main seismic code that deals with the assessment of seismic loads, and which defines the seismic zones and design factors. In the first edition of IS:1893-1962 (1962) the country was divided into seven seismic zones (0-VI), which was brought to 5 zones (I-V) after the Konya earthquake in 1967 (IS:1893-1970, 1970). This was further merged to the current division of 4 zones (II-V) since IS:1893(part 1)-2002 (2002), meaning that today all of India is subjected to seismic hazard. Zones IV and V cover most of the Himalayan range such as the states of Arunachal Pradesh, Assam, Sikkim, Uttarakhand, Himachal Pradesh, Ladakh and Jammu & Kashmir, as well as the Kutch Region in Gujarat in the west; in all these regions stone masonry is still practiced today. Since the very first 1962 edition it is stated that "in highly seismic areas, construction of a type which entails heavy debris and consequent loss of life and property, such as masonry - particularly mud masonry and rubble masonry, is best avoided." For construction features and material specifications the seismic code refers from its earliest editions to IS:4326-1967 (1968) "Earthquake-Resistant Design and Construction of Buildings", IS:1905-1961 (1962) "Masonry Walls" and to IS:1597(part 1)-1967 (1967) "Construction of Rubble Stone Masonry". After the 1988 Bihar earthquake in Nepal near the Indian border, more attention was needed for low-strength brickwork and stone masonry. For stone, this resulted in a division between IS:4326-1993 (1993) covering rectangular stone units related to IS:1597(part2)-1992 (2018) "Construction of Ashlar Stone Masonry"; and a newly introduced code IS:13828-1993 (1993) "Improving Earthquake Resistance of Low-Strength Masonry Buildings", for random rubble stone masonry with cement-sand mortar.

Its latest (reconfirmed) version with amendments IS:13828-1993 (2018) divides all buildings into categories, based on the seismic zonation factor Z and the building importance factor I. The highest Building Category E requires maximum provisions for strengthening, whereas the lowest category B requires the least. The code states that low-strength masonry constructions "should not be permitted"

for important buildings with $I \geq 1.5$. This concludes that school buildings in rubble stone masonry are not allowed to be built anywhere in India, although the word "should" weakens this statement. Houses are not permitted in category E (zone V), and "should preferably be avoided" in category D (zone IV). When using cement-sand mortar not leaner than 1:6 and with the inclusion of through-stones in the walls, no special seismic provisions are considered necessary for category B (zone II). As a result for housing designs, seismic specifications only need to be applied in category C (zone III) such as: Maximum building height is 2 stories plus attic, maximum free wall span 5.0m, maximum floor-to-floor height 3.0m and minimum wall thickness 0.35m. The minimum dimensions for masonry in corners (230mm), piers (450mm) and maximum percentage of openings (46% in ground floor and 37% in first story) are more generous than in Nepal, due to the restricted application in zone III only. Horizontal bands must be included at 3 to 4 levels (always roof and lintel, plus gable band on masonry gables, plus plinth beam on soft soils) and vertical bars only at critical wall connections (and in jambs when openings exceed the recommended dimensions). Mortar should be cement-sand in the ratio of 1:6 with minimum compression strength of 3.0N/mm^2 at 28 days according to IS:1905-1987 (2017), although in IS:13828 even mud mortar is allowed, but with stricter rules for building heights. However, it is important to note that according to the latest seismic code IS:1893(part 1)-2016 (2016), a seismic verification is always required, even in zone II with very low seismicity and a design acceleration factor Z/2 = 0.05g.

Like Nepal, the Indian codes are not mandatory from the state level. The current National Building Code of India IS:SP7-2016 (2016) has incorporated the latest seismic standards, but this code itself indicates that "it is non-statutory in nature and is intended to serve as a model for adoption by Public Works Departments, local bodies and other construction agencies." In urban areas it is nowadays common that banks require certain proof of code compliance to obtain a housing loan, thus giving the Indian seismic codes a status "between desirable and mandatory."

3.2.3 Pakistan

Pakistan has never had any provisions for stone masonry, nor for low-strength masonry in general, such as in India and Nepal. As early as the Quetta Building Code of 1937 (QBC-1937, 1937), developed after the very heavy and damaging 1935 Quetta earthquake (then part of the British Indian Empire), it is clearly stated that "dry masonry without mortar is strictly forbidden and stone boulders may on no account be used". This statement is repeated in the Quetta Building Rules of 1976 (G.P.(Q)23-3,100-10-77, 1976). The first Pakistan Building Code BCP-86 (1986) was presented as an "advisory document" and not enforced as a mandatory requirement. After the devastating 2005 Kashmir earthquake, the building code was upgraded with a focus on seismic design of buildings, whilst dividing the whole country into five seismic zones (BCP-SP-07, 2007). However, the seismic provisions and the masonry chapter are mostly verbatim copies of chapters 16 and 21 of the Uniform Building Code of 1997 (UBC-97, 1997), meaning that the information does not cover local practices, and as of today is more than 20 years old. The masonry section about empirical design contains word-for-word copied sections of the Indian Standards IS:4326-1993 (1993) and IS:1905-1987 (1989), which are specifically meant for regular sized stones (Ashlar), and currently more than 30 years old. Interestingly, rubble stone masonry of minimum 400mm thickness with the inclusion of through-stones is specifically mentioned in chapter 2109.10 of UBC-97. Therefore, it is surprising that of all articles this one was not copied into the Pakistani code. Even better would have been the inclusion of IS.13828 for low-strength masonry, as stone is still widely used in the northern parts of the country, especially in Gilgit-Baltistan province. In 2015 it was estimated that roughly 5% of the total building stock of

Pakistan continues to be built with stone (Lodi, 2015), which is around 1.25 million units, mostly located in the Karakoram mountain range which is part of the Trans-Himalayan region. If Pakistan has deliberately excluded rubble stone masonry from their code, then it must be questioned whether this represents the current practices and actual needs, at least for a significant part of the country. With that, the code also excludes other interesting traditional techniques, such as "Bhatar" which consists of dry-stacked loadbearing stone walls with horizontal timber lacing (Carabbio et al, 2018), or "Dhajji Dewari", wooden loadbearing frames with stone infill (Hicyilmaz, 2011). Structurally both systems behave different than nominally reinforced loadbearing masonry, but these techniques have resisted the 2015 earthquake very well.

3.2.4 Afghanistan

A 2003 governmental-issued construction manual estimated at the time that "more than 90% of the country's building stock are non-engineered constructions, made of mud-bricks and stone" (MUDH, 2003). No recent figures were found, but stone masonry is still abundantly practiced all over Afghanistan, such as in the seismically active Hindu Kush mountain range. Due to decades of conflict and a lack of governmental regulatory systems, Afghanistan did not have a unified building code until 2012 and engineers freely used locally issued guidelines and (former) Soviet and Indian codes, such as 1983-7-II (1983) and 1982-102-1 (1982), which were partial translations of the Russian code SNiP II-A.12-69* (1977) and the Indian code of practice IS:4326-1976 (1977). These allowed buildings up to 8m height in seismic Intensity zone 8, for masonry category 3 which includes irregular shaped stones (explained in more detail in the Russian section). The first mandatory Afghan Building Code (ABC-2012, 2012) however, is basically a collection of literally copied segments of the US codes IBC-2009 (2009) for structural requirements, ASCE/SEI-7 (2010) for design loads, and refers to ACI 530/530.1-11 (2011) for masonry. The masonry chapter defines that stone masonry units must conform to ASTM C568/C568M (2015) for limestone, ASTM C615/C615M (2018) for granite and ASTM C616/C616M (2015) for sandstone units. As these standards are exclusively for dimensioned stone, the Afghan code completely rules out the use of rubble stone for building purposes, which does not serve the current (non-engineered) construction needs and practices in the country.

3.2.5 China

China has a long historic culture of stone masonry which has been practiced for many centuries. For instance, Xizang Province (Tibet) borders the Himalayan Range, and Xinjiang Province is crossed by the Altay, Tian Shan, Kunlun Shan and Karakoram Mountains. China has also been prone to some of the most devastating earthquakes in history. Before the 1974 trial version of the first Chinese seismic code, China mainly followed the Russian codes. The country is divided into Seismic Fortification zones, and every building in zone 6 or above must be designed to resist earthquake motions. The earliest codes such as TJ 11-78 (1979) did not cover stone masonry, but all revisions that followed, starting with GBJ 11-89 (1993), have included a separate chapter with sections for earth, wood and stone buildings, which is still included in the most recent seismic code GB 50011-2010 (2016).

China uses a variety of stone types for masonry, as clearly explained in the "Standard for Building Material in Villages and Towns" (CECS 317:2012, 2012). It distinguishes four types of Ashlar with different degrees of dressing, being fine, semi-fine, coarse and very coarse. It further categorizes two types of rubble stone; flat rubble stone, which is minimum 150mm thick and has two sides that are roughly parallel, and irregular rubble stone. The latter is prohibited for constructing buildings in seismic areas, and so are round river boulders.

Regarding building typology, Standard GB/T 33735-2017 (2017) for "Avoiding Earthquake Danger for Schools" refers to the National seismic code GB 50011. However, its section for stone only covers low-rise buildings in ashlar masonry with concrete floors, meaning that rubble stone masonry buildings (with wooden floors) are ruled out. Along with that, school buildings in stone masonry are not allowed in any case due to certain design specifications for classrooms and requirements for indoor environment, as dictated in the "Code for Design of Schools" (GB 50099-2011, 2010). Further, the minimum demand for daylight in classrooms is specified in the design regulation for rural school buildings (Construction Standard 109, 2008), recommending a minimum ratio of glass surface versus floor area of 1:6. This results in too large openings which exceed the limitations of stone walls (and of general masonry walls as well). For all the above reasons, schools in China are currently predominantly constructed with reinforced concrete frames.

For houses on the other hand, China has published a "seismic technical specification" for construction of buildings in rural towns and villages (JGJ 161-2008, 2008). In this code, flat rubble stone houses with wooden roofs are allowed up to one story in zone 7, with a maximum height of 3.6m from ground level to halfway the gable. Minimum wall thickness is 400mm, maximum cross-spacing of walls 11m, and minimum lengths of corner masonry and piers are 1m. The total length of openings should not exceed 25% in cross-walls with a maximum length of 1.5m per opening, and 50% in longitudinal walls with a maximum of 1.8m. Reinforced concrete tie-beams must be included on top of the foundation and at roof level, as well as steel bar stitches in corners and junctions at 500-700mm intervals. The code further details specific connections between elements, stiffening of the roof structure, and laying patterns of the stones. China has developed a National Atlas of building designs, including a chapter with plans, sections and details of stone houses, that follow all the above-mentioned seismic design rules, material specifications and construction guidelines (08SG618-4, 2008).

3.3 Rubble Stone Masonry in Central Asia and The Caucasus

The countries stretching from the borders of China toward the Black Sea all belonged to the former Soviet Union and include areas with severe seismicity. Central Asia consists of five states known as "the Stans" which are Tajikistan, Kyrgyzstan, Turkmenistan, Uzbekistan and Kazakhstan, of which the main mountain ranges are shown in **Figure 14**. The Caucasus includes Russia, Azerbaijan, Georgia and Armenia. Until the dissolution of the Soviet Union in 1991, all countries followed the State standards (GOST) and the unified system of mandatory Construction Rules and Regulations (SNiP), sometimes with the addition of Regional Norms. After 1991 these countries started developing their own regulations, although most are still very similar to the Russian codes and are published bi-lingual (local language and Russian). The seismic rules apply to the design of buildings and structures at sites with seismicity of 7, 8 and 9 points, as defined on national seismic hazard maps that are based on the MSK-64 intensity scale (Medvedev and Sponheuer, 1969), although some countries have switched to a probabilistic seismic hazard analysis approach (Armenia, Kyrgyzstan).

3.3.1 Russia

To understand the role of stone masonry in all (former) Russian territories, one needs to go back to the definitions in the earliest codes of the 1950s. The material code SNiP I-A.1 (1955) makes a clear distinction between natural stones for wall masonry, being "stones of the correct form" such as sawn, chipped or cut shell limestones, and volcanic tuffs and other local light rocks with standard sizes; versus

"pieces of irregularly shaped rubble stone from local rocks" such as limestone, dolomites or sandstones. The subsequent material code SNiP I-B.8-62 (1962) further explains that "flattened or broken stone" (rubble) is obtained from either direct splitting of boulders, or by sorting of fractions from blasted rock. It further states that "for above-ground walls, sawn and chipped wall stones of the correct form are used. Rubble stone is allowed for masonry walls of agricultural, non-residential and industrial buildings."

In the seismic codes this is reflected as follows. Until the 1970s all masonry was divided into four strength classes. Rubble stone masonry was explicitly mentioned, as in PSP 101-51 (1951) which ranks the use of "natural stone of irregular shape" in categories 3 and 4, depending on mortar type. Category 3 masonry must meet a minimum "ultimate axial tensile strength" of 60 kPa, and category 4 at least 30 kPa. The next code SN 8-57 (1958) adds that for buildings in areas with estimated seismicity of 8 and 9 points, it is recommended to use masonry weighing no more than 1900 kg/m^3 (this includes most types of sawn stones); whereas masonry above 1900 kg/m^3 goes down one category (basically all types of rubble stone). This means that from an early stage, the codes refer to the lighter stone masonry types consisting of units with rectangular shapes. In 1969 (SNiP II-A.12-69*, 1977) masonry is reduced to just 3 categories, but still with an explicit mention of rubble stone.

Since the 1981 edition (SNiP II-7-81*, 1989) until today just 2 categories remain, with strengths over 180 kPa and between 180-120 kPa. For natural stone units, only "stones or blocks made of shell rock, limestones or tuffs" are allowed, but without any description of the shape or dimensions. These requirements were described in the State Standard GOST 4001-66 (1967), for sawn wall stones with "a rectangular parallelepiped shape with straight edges and regular faces." Therefore, and with the older codes in mind, we must assume that the 1981 seismic clauses refer to dimensioned stones only, and that rubble stone masonry is no longer allowed in the Russian seismic codes since. But in fact, this is no longer clearly described or specifically mentioned.

It is noteworthy that the earliest codes of the 1950s and 1960s had included a quite elaborate chapter about rural construction with earthen materials, which is still present in most recently updated seismic code SP 14.13330.2018 (2018). Unfortunately, the technique with rubble stone was never added to these clauses. On the other hand, the most recent and updated version of GOST 4001-2013 (2014) for natural stones has reintroduced rubble stone for the first time since the 1980s, but so far this has not lead to a renewed attitude toward rubble stone masonry in the seismic nor masonry codes. Similar to China, schools are not allowed these days due to specific requirements for comfort and daylight, but since these regulations were introduced only recently (SP 52.1330.2016, 2017), the codes in the former Russian states do not refer to such rules yet. The following paragraphs explain how the former Soviet countries deal with stone masonry today, except for Kazakhstan where this technique traditionally was not used.

3.3.2 Tajikistan

Tajikistan is extremely mountainous, with mountains covering 93% of its surface, of which more than half are situated above 3,000m. Centrally located are the Pamir Mountains and all borders are surrounded by mountain ranges, such as the Hindu Kush with Afghanistan, Tian Shan with China, the Alay Mountains with Kyrgyzstan, and the Turkestan Range with Uzbekistan. Around 70% of the population lives in rural and mountainous areas, where the main construction type consists of self-built

single-family houses in stone or mud-bricks (UNECE, 2011). The whole country has a very high seismic risk and Tajikistan is mapped in just 3 intensity zones of 7, 8 and 9 points. Contrary to the Russian and most neighboring codes, the masonry chapter of the first post-Soviet Tajik seismic code MKS CT 22-07-2007 (2007), as well as its revision SNiP RT 22-07-2018 (2019), does not explicitly rule out rubble stone, as it only "recommends" that stones must be of regular shape. With this minor adjustment stone masonry is allowed, even in the highest risk zone of 9 points. Still, lower-strength masonry of category 2 must meet a minimum "ultimate axial tensile strength of 120 kPa", which may be difficult to determine (or understand) in the rural areas. For zone 9 (on average soil) the code describes maximum building dimensions of 45m length and 2 stories height, and maximum 6m between cross-walls for masonry category 2 (or 9m for category 1, which is far more generous than the Asian codes). Maximum width of openings is 2.5m, minimum lengths for corner masonry is 1.8m and 1.55m for piers. The minimum ratio of the length of all openings divided by the length of the wall piers must be >0.75 for category 2. Wooden floors are allowed and the code further describes the inclusion of a continuous reinforced concrete band at floor or roof level, and wire mesh reinforcements in the horizontal joints at certain intervals, whilst vertical reinforcements are recommended and only mandatory in designs with complex plan configurations.

3.3.3 Kyrgyzstan

Kyrgyzstan is also characterized by a mountainous landscape, with roughly two-thirds of its population living in the rural and mountain areas. The housing stock mainly consists of single-family masonry buildings, mostly in adobe construction (Pittore and Parolai, 2016). Although figures were not found, it is expected that stone masonry is still practiced in the Tian Shan Mountain range at the border with China and the Alay and Turkestan ranges near Tajikistan, although to a lesser extent compared to Tajikistan. Kyrgyzstan had developed its first national seismic code in 1994 based on the Russian code and revised it twice. The 2009 version SNiP KR 20-02:2009 (2017) only allowed masonry that is reinforced with horizontal and vertical concrete elements, without specifying stone materials. However, the latest 2018 revision SN KR 20-02:2018 (2018) only allows stones of regular shape, thus ruling out rubble stone masonry. It is further noted that for determination of seismic loads, Kyrgyzstan has switched to calculation models that follow Eurocode. Kyrgyzstan is subject to a very high seismic hazard with estimated PGA > 0.6g.

3.3.4 Turkmenistan

Turkmenistan has a high seismic risk at its border with Iran. Roughly half the population lives in rural areas (World Bank, 2020), but no recent data was found on construction practices in those regions. Traditionally, adobe and earthen structures were most common, with some sporadic examples of stone masonry in the Köpet Dag Mountains. The masonry chapter in the first Turkmen seismic code SNT 2.01.08-99 (2000) is nearly identical to the Russian code of 1981, which does not cover rubble stone. However, one clause allows one-story buildings in rural settlements in zone 7 to be built with adobe, soil blocks and "other low-strength materials." Possibly for these, the code has included the third strength-category for masonry (between 120-60 kPa). The appendix with building classifications defines type 1b) as "houses with walls made of earthen bricks or rubble stone, with a light wooden roof", although no further details or dimensions are given. Further, when constructing on rock soil, the designs class goes down with one point from intensity zone 7 to 6, for which no seismic verification is required.

3.3.5 Uzbekistan

In Uzbekistan around half of the population lives in rural settings, such as the mountainous areas bordering Kyrgyzstan and Tajikistan, which have a high seismic risk. Here, the main traditional materials for construction are adobe and stone, for self-built privately-owned houses (Kaufmann et al, 2004), and also for school buildings (Nurtaev et al, 2017). The masonry chapter of the first post-Soviet seismic code KMK 2.01.03-96 (2004) mentions only the lighter natural stones types of shell rock, limestones or tuff, and explicitly mentions these must be of regular shape. However, in the 2004 amendment an extra clause is added to the separate chapter for "low-rise buildings with low-strength materials" such as adobe and wood: "For the construction of one-story buildings it is allowed to use natural stone with anti-seismic measures, developed according to special technical conditions agreed upon by the State Architects of the Republic of Uzbekistan." Uzbekistan is working on a revision of their seismic code which is expected to be published in the next few years. Hopefully, this updated version will include these technical details, and addresses constructions in rubble stone according to the current needs in the mountainous areas of the country.

Figure 14. *Main mountain ranges of the Caucasus region and the Middle East (original source: Natural Earth raster + vector map).*

3.3.6 Azerbaijan

Roughly 60% of the surface of Azerbaijan is covered by mountains, such as the Greater and Lesser Caucasus Ranges and the Talysh Mountains bordering Iran. All mountain ranges of the Caucasus are shown in **Figure 14**. The country is assigned to just 2 very high seismic hazard levels; intensity zones 8 and 9. Traditionally, stone masonry has been practiced widely with many examples of complete villages built with stone walls and wooden reinforcements. It is expected that the technique is still

practiced in the rural and mountainous areas in Azerbaijan and the Nakhchivan Autonomous Republic. However, the first seismic code AzDTN 2.3-1 (2014) does not reflect this culture as the masonry chapter is an almost identical copy of the 1981 Russian seismic code, which only describes dimensioned stone. No specific or extra clauses are added for rubble stone masonry.

3.3.7 Georgia

Georgia is wedged in between the Greater Caucasus Mountains on the borders with Russia and Azerbaijan, and the Lesser Caucasus Range on the southern border with Armenia. The country still has a rich culture of stone masonry that is reflected in their first National seismic code PN 01.01-09 (2012), which includes a separate chapter for buildings made of local materials. In here, rubble stone buildings of 2 stories height are allowed in seismic zone 7 and 8, with a maximum cross-wall spacing of 6m. (This contradicts a previous table which allows 2 stories in zone 7, and 1 story in zones 8 and 9 as well). Walls must be strengthened with 2 horizontal rows of bricks for every 60-80cm wall height, and a continuous tie-beam at floor level. Floors must be made of wooden members, the roof structure must be properly anchored to the walls and made as stiff as possible. No further dimensions are given in this section, however, if we follow the general masonry chapter this results for zone 8 in a most generous maximum length of 80m between separate building units. Bearing in mind the original Russian codes, it is likely that these dimensions are meant for regular masonry with dimensioned stone, and not for rubble stone masonry. Dimensions for corner masonry, piers and openings are exclusively mentioned for brick masonry; for stone masonry verification through calculations is needed. A minimum wall thickness is also not mentioned, but traditionally rubble stone masonry walls in Georgia are between 60-80cm thick. The minimum strength requirement for cement-sand mortar is grade 25 for normal conditions and grade 50 in areas subject to temperatures below 0°C. Grade 25 means an ultimate compression strength of 25 kg/cm^2 which roughly equals M2.5 mortars (2.5 MPa). It must be noted that Georgia is currently in the process of adopting Eurocode and development of a National Annex to Eurocode 8

3.3.8 Armenia

Armenia also has a rich historic culture of stone masonry, which is still practiced today. Roughly one-third of Armenia's dwellings are in the rural and mountainous areas. Most of these mainly single-family houses are built with volcanic or dressed tuff stones, the traditional building material of Armenia (UNECE, 2017). The sawn stone types as mentioned in the Russian codes since the 1950s often come from Armenia, such as Arctic, Ani and Yerevan tuff. Since medieval times 50cm thick loadbearing walls were built of a stone cladding type called "Midis", with a double layer of roughly cut stones, filled with mortar and pumice in the middle. The technique is still explained in the masonry code RABC IV-13.01-96 (1996), in which also standardized sizes and wall thickness between 19-39cm are mentioned for fully dressed stones, as mainly used today.

The third-and-about-to-be-published (as of February 2021) version of the Armenian seismic code RABC 20.04_ (2020) has become more conservative toward masonry in general, compared to its predecessor RABC II-6.02-2006 (2011). The code divides the country into three seismic zones (1-3) and distinguishes four soil types (profiles I-IV). The masonry chapter is quite different from the Russian code and specifically allows rubble stone masonry. For type III structural loadbearing masonry with horizontal (steel net) reinforcements, no difference is made between bricks, dimensioned stones or rubble stones, for as long as a minimum wall strength requirement (120 kPa) is met. In the most unfavorable scenario (zone 3, soil profile IV) for masonry type III, a maximum building ratio of 1:3

(width versus length) is allowed, with a limitation of 2 stories height and 6m spacing of cross-walls. The maximum width of openings is 2.0m, corner masonry has a minimum length of 2.5m and piers minimum 2.2m. Horizontal concrete bands at floor level are mandatory, but as floors must act as rigid diaphragms, wooden floors are not allowed. This latest revision specifically adds that for school buildings, only monolithic concrete slabs are allowed. All other rules apply for both houses and schools, although a recent guideline (not mandatory) for restauration and new construction of school buildings, recommends only reinforced concrete and steel frame structures (Applied Technology Council, 2017). It must be further noted that, although rubble stone is allowed, it is not used very often, as in Armenia the primary choice for stone wall material is dimensioned tuff stone blocks.

3.4 Rubble Stone Masonry in the Middle East

Most countries bordering or located on the Arabian Plate are either subject to relatively low seismicity levels, or they mainly follow international seismic codes. For instance, the Lebanese code NL-135 (2012) refers to either the French or US-based codes (but intends to adopt Eurocode), the Syrian code is basically a translation of UBC-97 (SAC-2012-2, 2013), Israel goes with ASCE-7 (SI-431-1995, 2013), Iraq embraces the 2012 International Building Code (IBC) (ISC-303, 2017) and Oman largely follows Eurocode (OSDC-2013, 2013). In Jordan, a very common wall system for low-rise buildings consists of veneer-like cut stone blocks that are back-filled with plain concrete, and confined with horizontal and vertical reinforced concrete elements; but structurally this is a different type of construction than NRM (Al-Nimry et al, 2003). In Saudi Arabia stone was used a lot in the past, such as in the southern provinces of Saheer and Al Bahah, but these days it is basically no longer practiced. They mainly follow IBC and mention in its masonry code that stone masonry is only allowed in their lowest Seismic Design Category A (SBC 305-CR, 2018) with very low seismic risk (<0.07g). Yemen, with its rich history of stone and earth block masonry, does not have a seismic nor masonry code at all. Therefore, the two remaining countries of interest in this region are Turkey and Iran. The main mountain ranges of the Middle East are shown in **Figure 14**.

3.4.1 Turkey

Turkey has a long and rich history of construction using stone masonry, such as fully loadbearing walls with wood-lacing, or a system of braced wooden frames with stone-infill called “hımış”. The country is frequently subjected to destructive earthquakes. The first provisional Turkish seismic code, published after the devastating 1939 Erzincan earthquake, was basically an adapted translation of the 1937 Italian code (RDL n.2105, 1937). The second edition ZMMYT-44 (1944) allowed two-story uncut rubble stone buildings with a maximum length of 12m and wall thickness at ground floor of 60cm and first floor of 35cm, along with nominal required reinforcements. Interestingly, in the 1968 version ABYYHY-68 (1968) the building height was increased to 3 stories, but then again 7 years later this was drastically reduced to just one floor (ABYYHY-75, 1975).

The rules for stone remained the same until the code of 2007 (DBYBHY, 2007), but since the most recent revision of 2018, rubble stone masonry is no longer allowed (TBDY, 2018). The masonry chapter refers to the European norms and TS EN 771-6+A1 (2015) in particular, meaning that natural stone units must follow the requirements for dimensioned stones. On top of that, it is emphasized that rubble stone, among other materials like pumice and adobe, “shall not be used as bearing wall

material". This is unfortunate, as reconnaissance reports show that rural one-story stone houses with traditional nominal reinforcements and light roofs behaved well under seismic motion, such as during the 2003 Bingöl (Ozcebe et al, 2003) and 2011 Van-Erciş earthquakes (Aydan et al, 2012).

3.4.2 Iran

Iran is situated in a very active part of the Alpine-Himalayan seismic belt. Almost the whole country, including several large mountain ranges, such as the Alborz, Zagros, Makran and Köpet Dag Mountains, falls within an active seismic zone numbered 1-4 on the Iranian seismic hazard map (Moinfar et al, 2012). Due to the predominant use of Unreinforced Masonry (URM) construction at that time, the first Iranian seismic code PBO-64 (1964) covered only "non-engineered" buildings such as loadbearing masonry with additional horizontal tie-beams. The first edition of the modern Iranian seismic code Standard 2800 (1987) made a clear division between engineered buildings (steel, concrete) and introduced a separate chapter for URM. The information in this chapter remained nearly identical for 28 years, but in the most recent fourth edition Standard 2800 (2015) it is renamed to "Provisions for Masonry Buildings with Ties." The chapter solely describes Confined Masonry with some alternatives for materialization including confined rubble stone masonry, which is achieving promising test results (Ahmadizadeh and Shakib, 2016).

Unreinforced masonry (or in this case URM but nominally reinforced) with cement mortar and a wooden roof is described in the Iranian masonry code NBRI-8 (2013). It allows rubble stone but only in the lowest seismic zone (PGA ≤ 0.20g), for buildings of maximum one floor above ground level with 3.5m height. The minimum wall thickness is 450mm and the building length may not exceed 2 times its width (or 25m), with maximum 4m cross-spacing of walls. Openings may not exceed 1.2m, piers must be minimum 650mm and corner masonry must be at least two-thirds of the height of the adjoining opening. One horizontal tie-beam is required at roof level, and vertical reinforcements are not necessary when all the above-mentioned dimensions are respected. Interestingly, for both URM (NRM) and CM, no seismic verifications are needed according to the Iranian seismic code. Moreover, neither seismic nor masonry code makes a difference between buildings of medium (houses) and high importance (schools). However, it must be noted that all schools are designed and constructed by the "Organization of Renovation, Development, and Equipping of Schools" under the Ministry of Education, who is in a position to deviate from the codes, and who may apply different (possibly stricter) regulations for the urban or rural settings.

3.5 Rubble Stone Masonry in Northern Africa

Most of the African Continent has very low seismicity, to basically no activity across the Sahara and central parts. However, some northern countries that border the Mediterranean Sea are subject to significant earthquake risks. Tunisia and Libya have not yet developed national seismic codes up to date. Due to 130 years of French colonial rule, they mostly follow the older French codes such as DTU Règles-PS-92 (2004), which mentions both cut and rubble stone as a possible masonry material, but only for Confined Masonry structures. The Egyptian building code solely describes the use of dimensioned brick and block-shaped stones (ECP-204, 2005). The main mountain ranges of Northern Africa are shown in **Figure 15**.

Figure 15. *Main mountain ranges of North Africa, East and South Europe. (original source: Natural Earth raster + vector map).*

3.5.1 Algeria

Algeria has possibly published the first seismic code ever, with regulations for reconstruction as ordered by Governor (Dey) Ali Chaouch after the 1716 Algiers earthquake (Chesneau, 1892). After the 1954 Chlef earthquake, a provisional set of recommendations was published (AS55, 1955) which described the use of Confined Masonry for seismic areas, but without materialization of the masonry units. It was followed by the French code DTU Règles-PS-69 (1970) with similar recommendations. After the destructive El Asnam earthquake in 1980, Algeria published its first national and mandatory seismic code (RPA-81, 1981). It was revised in 1999 and directly amended after the very damaging 2003 Boumerdes earthquake into the current version RPA-99 (2003), which does allow rubble stones; but only for CM buildings, up to 3 stories in highest seismic zones III and IIB, and 5 stories in zone I.

3.5.2 Morocco

Morocco published a local code right after the highly devastating Agadir earthquake in 1960 (Normes Agadir, 1960), which allowed only confined rubble stone masonry for buildings up to 4 stories. The code included very detailed descriptions for types and dimensions of stones and masonry patterns. In their latest code RPS-2000, (2011) rubble stone masonry with cement mortar is allowed in three techniques (URM, CM, RM), all with a maximum of 2 stories regardless of the seismic zoning. For URM unfortunately, no further dimensions nor details are given, in contrast to a separate code that Morocco has published for earthen structures in seismic areas (RPCTerre-2011, 2013). It resembles the Nepali and Indian codes for NRM; however, it only covers rubble stone with mud mortar. Lastly, it is important to note that nearly all of Morocco (except Al Hoceima in the north and Agadir in the south) has low to very low seismic risk levels (Cherkaoui and El Hassani, 2012). This almost negligible risk includes the complete Atlas Mountain ranges, where stone masonry is still broadly utilized.

3.6 Rubble Stone Masonry in Europe

Since 2004, the European seismic code EN 1998-1:2004+A1 (2013), commonly known as Eurocode 8, is the leading norm to which most European countries have committed. It describes a minimum required thickness of 350mm for URM shear walls with natural stone units, but only for moderate seismicity zones with a peak ground acceleration value for unreinforced masonry of $a_{g,urm} \leq 0.20$g, and with the addition of horizontal and vertical reinforcements (making it NRM). It refers to the masonry code Eurocode 6 (EN 1996-1-1, 2005) for specifications of the masonry units, which dictates that only dimensioned stones are acceptable, as further specified in EN 771-6:2011+A1 (2015) for "Natural Stone Masonry Units." This means that Eurocode clearly prohibits the use of newly built squared rubble and random rubble stone masonry structures in seismic areas. Countries that have adopted Eurocode are however allowed to deviate from the regulations through their National Annexes. The following paragraphs describe the historic application of stone masonry in the seismically active Eastern and Southern regions of Europe (**Figure 15**) and examines if countries currently allow rubble stone as a masonry material.

3.6.1 Romania

In their first seismic code P13-63 (1963) Romania mentioned the use of irregular shaped natural stones with cement-lime mortar for masonry, although its use was limited to ground floor buildings only. But after the powerful 1977 Vrancea earthquake, the use of stone for walls has been removed altogether from the seismic code P100-78 (1978) and masonry code P2-85 (1985) ever since. With that omission, a very nicely illustrated technical publication from 1979, one of very few manuals worldwide that was specifically drafted for stone masonry, became void as well (C193-79, 1979). Also, the most recent seismic code of 2013, which is harmonized with Eurocode 8, explicitly excludes stone masonry and explains this in the commentary as follows: "For stone masonry special regulations are required because the existing information, necessary for the seismic design, is incomplete or irrelevant. Experimental research is necessary and important, both at the level of the respective elements and the structural elements of this type of masonry" (P100-1, 2013). This means that on a positive note, further research may create new opportunities for stone masonry in the future.

3.6.2 Bulgaria

In Bulgaria lots of stone masonry is still seen, such as in the Rhodope Mountains, a region subject to high seismic levels. The first Bulgarian seismic code Decree n.15 (1947) allowed stone masonry for two-story buildings in the highest seismic zone IX, with a minimum wall thickness of 53cm and maximum wall-spacing of 12m, but without specification for the type of stones. The following code State Committee for Construction and Architecture (1957) specified that natural stones must be of regular shape (Ashlar) and this requirement has not changed up to the latest Bulgarian seismic code Ordinance RD-02-20-2 (2012), which only describes certain brick types for use as masonry unit. This current code is strongly influenced by Eurocode 8 but remains to be the main seismic code used in Bulgaria, as Eurocode 8 is only mandatory for structures of very high and national importance.

3.6.3 Former Yugoslavian Countries

Until the dissolution in 1992 into its currently 7 independent countries (Slovenia, Croatia, Bosnia-Herzegovina, Montenegro, Serbia, Kosovo and North Macedonia), the whole region used one unified seismic code with the addition of regional seismic hazard maps. After the very damaging 1963 Skopje earthquake in Macedonia, a temporary code SFRY-39/64 (1964) was drafted. It mentioned a few specifics for irregular stone masonry, such as a maximum height of 2 stories, and that the masonry must be reinforced or confined. After the 1979 Montenegro earthquake, the new code SFRY-31/81 (1981) was published. It was revised several times and new seismic maps for all regions (based on the MSK-64 intensity scale) were introduced in its latest version SFRY-52/90 (1990). It distinguishes three types of masonry: Ordinary (meaning Unreinforced), Confined and Reinforced. Ordinary masonry considers walls that are constructed with bricks, burnt-clay blocks or "other materials", with either cement-sand-lime or cement mortar with a minimum compressive strength of 2.5 MPa. All walls thicker than 19cm must be strengthened with horizontal tie-beams and vertical tie-columns, and floors must be rigid concrete slabs (or of equivalent stiffness). Although stone is no longer specifically mentioned, the code states that masonry must meet certain tensile strength requirements, if needed by proof of experimental testing. Provided that stone, or even rubble stone is allowed as "other material", then 2-story buildings with spacing of 7.5m between cross-walls of 38cm thickness are allowed in seismic zone VIII, without further calculations and regardless of the masonry type. With seismic verifications, confined masonry is allowed up to 3 floors in zone IX and 4 floors in zone VIII.

Currently, Bosnia-Herzegovina, Montenegro, Kosovo and North Macedonia are still in the process of adopting and implementing the Eurocodes (Athanasopoulou et al, 2019), therefore the 1981 version of the Yugoslavian code (plus revisions) is still valid in these countries. On the other hand, Croatia, Slovenia and recently also Serbia (RS-89/2019, 2019) have fully adopted the Eurocodes; the latter two without anything specific in their annexes for stone masonry, thus only allowing Ashlar stone masonry.

3.6.4 Croatia

Croatia deserves a separate section, being the only country in this region that has conducted research on the mechanical properties of stone masonry, as mentioned in the Yugoslavian code. As a result, it has added "roughly cut stone" with a minimum wall thickness of 450mm and minimum compression strengths for stone (30 N/mm^2) and mortar (5 N/mm^2) to its National Annex of Eurocode 6 (HRN EN 1996-1-1:2012/NA, 2012). When following their annex to Eurocode 8 (nHRN EN 1998-1:2011/NA, 2011) for URM with required nominal reinforcements, then "simple masonry buildings" in importance class II (houses) are allowed without mandatory verification, as follows: Maximum height depending on the acceleration at site (2 stories for $a_g = 0.30$g or 5 stories for $a_g \leq 0.20$g, both on rock soil) and a minimum given percentual area of shear walls. These values are more generous than the recommendations in Eurocode 8 itself. The length of a building between seismic gaps may not exceed 4 times its width, with a maximum spacing of cross-walls of 7m. Dimensions of wall elements (l) next to openings (o) must conform to a ratio of l/h(o) > 0.5, which roughly amounts to 1050mm next to doors. As stated at the beginning of this European section, Eurocode 8 recommends that URM is not used when the acceleration at site ($a_{g,urm} = a_g \cdot S$) exceeds 0.20g. Croatia has not defined such limit in their Annex, however, for buildings with higher importance such as schools, and URM buildings in areas with PGA>0.30g, a full seismic verification is required. In all cases, URM must be strengthened with a horizontal tie-beam at floor and roof level, and a floor type that provides adequate diaphragm action.

3.6.5 Albania

Albania is particularly interesting, as stone was not only used in the past, it is still practiced today at various places in the Northern and Southern Mountain Ranges. Their 2011 census showed that 88% of the countries' building stock consisted of brick or stone masonry (Novikova etal, 2015). Although Albania has adopted Eurocode, these regulations are not yet implemented. The translation of Eurocode 8 (RRTP-NRT-2004, 2014) states that its rules must be used in conjunction with the Albanian seismic code KTP-N.2-89 (1989), which may cause confusion as it is largely Russian-based. Effectively, most engineers still use the 1989 Albanian version. Its predecessor KTP-2-78 (1978) did allow masonry with irregularly shaped rubble stone in seismic zone 7, with a maximum building length of 10m and height of 5m. The 1989 code, however, has introduced building importance classes and only allows irregular stone masonry for small industrial and agricultural buildings, but no longer for schools and houses.

3.6.6 Greece

Greece is seismically one of the most hazardous regions of Europe, with a rich history of stone masonry. Their first seismic code BD-19/02 (1959) makes just one mention of "artificial or man-made natural stone", but without further detail. Greece never had a separate masonry code, and also their latest seismic code EAK2000 (2010) does not mention stone masonry. In 2014 Greece has decreed that for seismic design of buildings, either AEK2000 or Eurocode 8 is used (Decree 372–30.5.2014, 2014), which effectively rules out new applications of rubble stone masonry buildings.

3.6.7 Portugal

After the 1755 Lisbon earthquake, Portugal published what is believed to be one of the first seismic building code ever developed (Borges, 1960), but it took two centuries until the publication of its next and first official code. Traditional stone masonry is still seen at many places in the country, but the technique was only briefly mentioned in the 1951 General Regulation for Urban Buildings (RGEU, 1951). It described some basic dimensions for both cut, as well as irregular stone walls, and allowed masonry buildings up to 7 floors. It also mentioned that provisions should be made in earthquake zones, but these specifications were not published until the first official seismic code of 1958 (RSCCS, 1958), which divided Portugal's mainland into three seismic zones. It described that buildings with "strong masonry walls" and higher than 3 floors in the most severe zone A (and 4 floors in zone B), must be reinforced with concrete tie-beams, in which case seismic verification is not necessary. No further codes nor provisions were developed for masonry in general until the adoption of Eurocode, which rules out rubble stone.

3.6.8 Spain

In Spain, stone masonry has been used abundantly in the past, such as in the seismically active region of Andalucía. The preliminary Spanish seismic code PGS-1 (1968) only permitted Ashlar units for stone masonry, with the inclusion of certain earthquake-resistant features. The first official code PDS-1 (1974) had added dry-stacked rubble stone, as well as roughly cut Ashlar, but without mention of rubble stone masonry with mortar. Since 1994 stone masonry is no longer clearly specified in the seismic code (NCSE-94, 1995) nor the masonry code (NBE-FL-90, 1991), other than one specific restriction for dry-stacked stone masonry. Also, the Spanish National Annexes mention nothing different than is described in the Eurocodes.

3.6.9 Italy

In Italy, the mention of stone masonry in either Regional Regulations (RE/RD/RDL), Governmental Decrees (DM) and Technical Norms (NTC) goes back to the 19th century. After the 1883 Casamicciola earthquake, only single-story masonry buildings with light roofs were allowed in this region, either with ordinary bricks or tuff stones grinded into a parallelepiped shape (RE-09/01/n.212, 1884). This was revised in 1909 to single-story buildings with shaped or "properly broken" rubble stones and river boulders, with a maximum wall spacing of 5m, and reinforced either with concrete bands or with closely spaced horizontal courses of bricks at height intervals of 60cm (RD-18/04/n.193, 1909). The latter masonry type is called "muratura a pietrame listata" or simply "muratura listata", which is still included in today's code. Already since these earliest codes, the use of mud mortar was, and still is, strictly forbidden. In 1935 two seismic zones were introduced (RDL-22/03/n.640, 1935). The more severe zone 1 allowed muratura listata of two stories height with cross-walls at maximum spacing of 6m, and zone 2 allowed three stories with maximum 12m height and 7m cross-wall spacing. The wall thickness of the ground floor ranged from 40-75cm, depending on the seismic zone and the number of floors above. The maximum number of stories for muratura listata was reduced with one floor for each seismic category in 1962 (L-25/11/n.1684, 1962) and a continuous reinforced concrete band was added at all floor levels.

In 1987 Italy introduced its first official masonry code (DM-20/11, 1987) with a separate chapter for stone masonry. These rules are still largely incorporated in the latest seismic code NTC-2018 (2018), which only allows "simple" stone masonry buildings in the lowest seismic zones ($a_g \cdot S \leq 0{,}075$g). Here, three-story buildings are allowed with maximum wall spacing of 7m and minimum wall thicknesses of 400mm for muratura listata and 500mm for coarsely worked quarry stones; provided that the stones conform to certain mechanical characteristics for strength, compression and durability. Wooden floors and roofs are not specifically mentioned but are commonly used in Italian stone buildings in Italy. The horizontal rows of bricks can be replaced with continuous reinforced or unreinforced concrete bands. Although restricted to areas with a low seismic hazard, with these clauses the Italian national codes deviate from Eurocode.

3.7 Overview of National Seismic and Masonry Codes

This chapter summarizes the design specifications for those countries that still allow the technique of rubble stone masonry buildings with cement mortar and wooden diaphragms in seismic areas. It further highlights some overall observations of the national seismic and masonry codes that may need attention, for which suggestions and recommendations for improvement are given.

3.7.1 Summary of Design Specifications

Currently, the application of nominally reinforced rubble stone masonry (NRM) with cement mortar and wooden diaphragms in seismic areas, is only mentioned in the national codes of 15 countries in the world. However, 8 countries need to be excluded from further review for various reasons. In Turkmenistan and Uzbekistan, the technique is allowed, but only briefly mentioned without any further detail. In the countries that still use the former Yugoslavian code (Bosnia-Herzegovina, Montenegro, Kosovo and North Macedonia), the technique is "not clearly ruled out" and rubble stone is (possibly) classified under "other materials". But since these former Balkan countries are in the process of

adopting Eurocode, this will likely result in the rejection of rubble stone masonry in this region. Armenia must be excluded, because wooden diaphragms are prohibited, and their main construction material is dimensioned tuff stone blocks; rubble stone masonry is not commonly used. And lastly Italy, where rubble stone is still allowed, but only in zones with a very low seismic risk. This leaves 7 countries where the use of rubble stone masonry for buildings in highly seismic areas is still practiced and specifically allowed, for which the main requirements and design specifications are summarized in **Table 7**. These are Nepal, India, China, Georgia, Iran and Croatia. In Tajikistan the technique is not ruled out as it is only "recommended" to use cut stones, and is therefore added to the list; also because this is in line with the current needs and practices in the country.

Overall, it is observed that the allowed dimensions of building volumes and their individual elements vary greatly between the countries. Maximum building lengths between seismic gaps range from a ratio of L = 2W (or 25m) in Iran to 80m length in Georgia. The maximum number of stories ranges from just one in Iran and China to five in Croatia, which is a remarkable difference as each corresponding maximum acceleration at site is 0.20g (and 0.15g in China). There is also no agreement on the dimensions of openings (between 25-50% of wall length), minimum lengths of corner masonry (between 230-1800mm) and piers (between 450-1550mm), as well as methods and numbers of nominal reinforcements. Nepal requires concrete horizontal reinforcements at six levels (four beams or bands and stitches at two levels), China requires two beams and three to four rows of steel rod stitches (depending on story height), India only requires two beams when building on rock soil. All other codes require just one horizontal tie-beam at floor or roof level, with additional rows of bricks in Georgia. Inclusion of vertical reinforcements at critical connections is only required in India and Nepal. Most striking however, are the huge differences between maximum allowed design accelerations, ranging from just 0.08g in Indian zone III versus 0.52g on medium soils in Georgia. Moreover, it is observed that some countries are not taking the implications of different seismic hazard levels into account. For instance, the current design rules in Nepal are the same for all seismic levels, which may result in either excessively reinforced buildings in low seismic zones, or worse, in insufficiently reinforced buildings in highly seismic areas.

To visualize the most important differences, **Figure 16** shows the maximum allowed volumes in the maximum allowed seismic zones for houses and schools, including the horizontal reinforcements, according to the seismic codes of Nepal, India, China, Tajikistan, Iran and Croatia. Georgia is left out due to conflicting data in their code regarding the main dimensions. For the house a standard squared configuration of 4 rooms is taken. China allows the construction of square rooms spanning 11m, but at the same time this is also the limitation of the orthogonal wall length, meaning that the four rooms are placed in a row. For the school, a floor plan of classrooms that are placed in a row is chosen, which is limited to 3 spans in India and Nepal, just 2 in Iran and 4 rooms in Croatia. In India and Nepal, buttresses must be introduced to shorten the free-standing length of the walls. However, in both Nepal and India schools are either not recommended or governmental approval is needed. Overall, the differences in volume are enormous, especially in the highest seismic category. In Tajikistan, houses are allowed that are 8 times larger in volume, whereas for the school this difference is 20 times.

The huge differences between basically all design requirements are raising questions about the completeness and correctness, as well as the reliability and actual value of the knowledge in this field. The same was concluded after the literature review of practical manuals in the previous chapter, where the currently available information was perceived as highly confusing, contradicting and incomplete.

Table 7. *Main design requirements according to seven national seismic codes that currently allow nominally reinforced rubble stone masonry in seismic areas.*

Code Requirements for Houses and Schools in Rubble Stone Masonry	NBC 202:2015 (2015)	IS 13828:1993 (2008)	JGJ 161-2008 (2008)	SNiP RT 22-07-2018 (2019)	PN 01.01-09 (2010)	NBRI-8 (2013)	nHRN-EN.1998.1/NA (2011)
General							
Country	Nepal	India	China	Tajikistan	Georgia	Iran	Croatia
Seismic zones (low to high)	1 - 4	II - V	6 - 9 pt.	7 - 9 pt.	7 - 9 pt.	1 - 4	mapped
Houses (H) or Schools (S)	H, S[1]	H (S[3])	H	H, S	H, S	H, S	H, S*
Max. allowed seismic zone	–	III (IV[4])	7	9	? 8 or 9	1	–
Max. allowed acceleration	– (0.40g)[2]	0.08g (0.12g[4])	0.15g	0.40g	? 0.24g or 0.52g	0.20g	>0.30g* (0.20g[5])
Wooden floor/roof allowed	yes	yes	yes	yes	yes	yes	*
Volumes and Dimensions (in m)							
Max. ratio length (L) vs width (W)	L=3W	–	–	–	–	L=2W	L=4W
Max. length btw seismic gaps	–	–	–	45	80	25	–
Max. number of stories	2+attic	2+attic	1 sto.	2 sto.	? 2 or 1	1 sto.	5 or 2 st.[6]
Max. height of building	–	–	3.6	–	–	3.5	–
Max. unsupported wall length	4.5	5.0	11.0	9.0[10]	6.0	4.0	7.0
Max. height floor-to-floor	3.0	3.0	3.5	4.5	4.0 (H)	–	(h/t) < 9
Mortar ratio cement-lime-sand	1:6 c-s	1:6 c-s	>1 MPa	>5 MPa	M2.5/M5[7]	1:3/1:1:6	>5 MPa
Max. spacing buttresses (if req.)	3.0	4.0	–	–	–	–	–
Walls and Openings (in mm)							
Min. wall thickness	350	350	400	–	–	450	450
Max. wall thickness	–	450	–	–	–	–	–
Max.% openings in wall (1 sto.)	30%	46%	50%[8]	ratio 0.75	–	50%	% A_{floor}
Max.% openings in wall (2 sto.)	30%	37%	–	ratio 0.75	–	–	% A_{floor}
Max. length of openings	–	–	1800[8]	2500[10]	–	1200	% A_{floor}
Min. distance corner to door	600	230	1000	1800[10]	–	2/3h (d)	(l/h)>0.5
Min. distance corner to window	600	230	1000	1800[10]	–	2/3h (w)	(l/h)>0.5
Min. size piers between openings	600	450	1000	1550[10]	–	650	(l/h)>0.5
Nominal reinforcements							
Horizontal concrete bands per story	min. 4	min. 2	2	1	1	1	1
Stitches(s), mesh(m), brick bands (bb)	min. 2s	–	min. 3s	m	bb	–	–
Vertical bars[9] (b) or rc posts (rp)[9]	rp	b	–	n.mand.	–	–	–

- = Not mentioned in the publication
? = Confusing or contradicting information
* = Not ruled out, must be calculated or modeled
n.mand. = Mentioned but not mandatory
[1] Regional / governmental approval needed
[2] Highest value on the Nepali seismic hazard map
[10] Depending on masonry quality; 9m for category 2
[3] Not clearly ruled out: schools "should not be permitted"
[4] Not clearly ruled out: zone IV "should preferably be avoided"
[5] Maximum recommended value in Eurocode 8
[6] 5 stories for $a_g \leq 0.20g$, 2 stories for $a_g = 0.30g$
[7] In areas with temperatures below 0°C
[8] In longitudinal walls; in cross-walls this is 25% and 1500mm
[9] Only when maximum dimensions of openings are exceeded

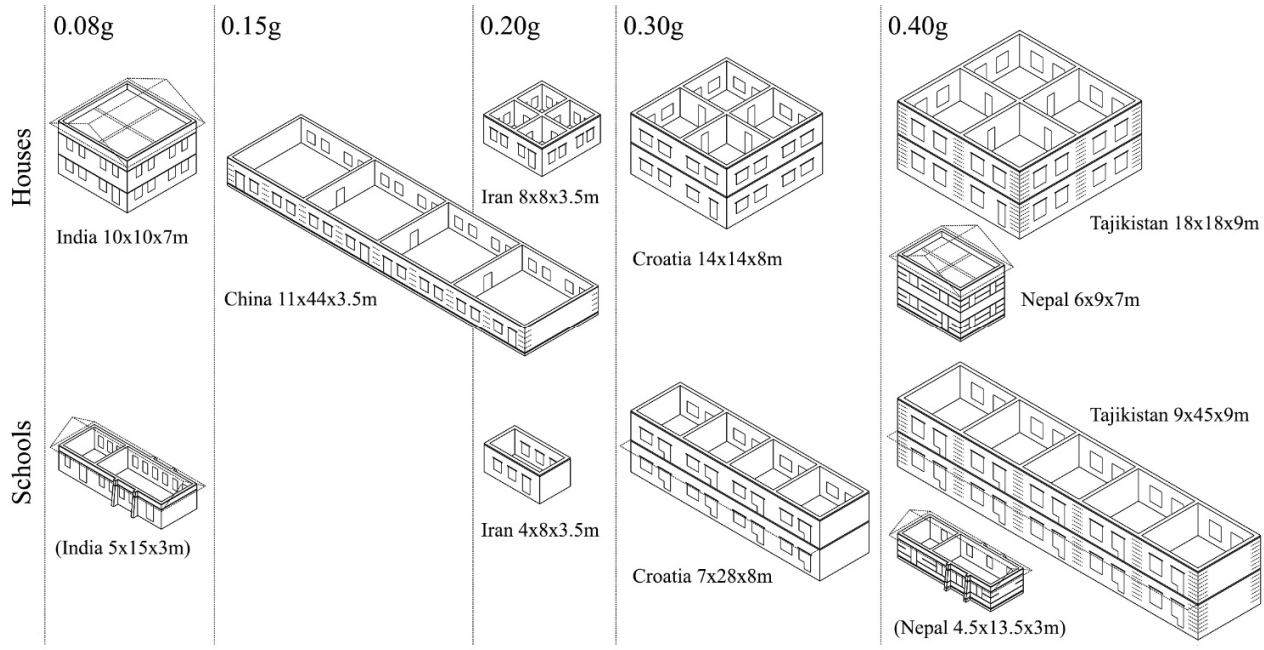

Figure 16. *Maximum allowed volumes in maximum allowed seismic zones for housing and school designs according to seismic codes of Nepal, India, China, Tajikistan, Iran and Croatia.*

3.8 Observations and Recommendations

The review of national seismic and masonry codes has brought several further issues to light. Firstly, it is seldom clearly described what type of masonry construction is addressed. It is therefore proposed to internationally adopt loadbearing Nominally Reinforced Masonry (NRM) as a fourth category. The main reason is to make a clear distinction between NRM and "truly" Unreinforced Masonry (URM), next to Reinforced Masonry (RM) and Confined Masonry (CM). It is also important that codes clearly mention what stone types are allowed, with a clear difference between random rubble, and cut stones with brick-like dimensions. This is particularly the case for all Russian-based codes in Central Asia and the Caucasus, which indirectly refer to clauses that were developed in the 1950s for dimensioned tuff stones. During the many revisions that followed, the stone properties are no longer specifically mentioned and therefore leaves room for interpretation. Such as the Uzbek code KMK 2.01.03-96 (2004) which has copied clauses for regular shaped stones from the Russian seismic code of 1981 (SNiP II-7-81*, 1989). However, it is generally assumed that these relate to rubble stones, since this is the most generally used construction material, whereas dimensioned tuffs were never common at all in Uzbekistan (Nurtaev, 2019). The Indian seismic code IS:1893(part 1)-2016 (2016) also leaves room for interpretation as stone masonry "should preferably be avoided" in seismic zone IV, and construction of schools "should not be permitted". The overall point is: Any possible misinterpretation can easily be avoided by adding a clear line in the codes, which specifically states whether rubble stone masonry is allowed or not; and to what types of buildings and structures it applies.

Secondly, it is praiseworthy that a few countries have developed separate codes for "non-engineered" construction types, such as the Indian code IS:13828-1993 (2008). Unfortunately, this code has become very difficult to read and interpret, due to its many amendments and references to other codes outside the publication, such as for foundations, stone types and seismic provisions. Some data had to be found in a footnote which referred to another footnote (as detailed in chapter 2). Also, it is questionable whether sizes, dimensions and details for thinner brick walls can be freely interchanged with those for thicker rubble stone walls, as also observed in the Nepalese "non-engineered" codes (NBC 202:2015, 2015). Such interchanging of incompatible information may also be the case in the seismic code of Georgia (PN 01.01-09, 2012), where the very generous design specifications are presumably meant for brick masonry, rather than for rubble stone buildings. To enhance clarity and avoid further confusion, the proposed solution is to develop a stand-alone code that is specifically intended for NRM rubble stone buildings in cement mortar. Block and brick masonry behave differently than stone masonry, and a clear distinction must be made between different types of mortars, such as cement or mud. It is further recommended to structure the national codes for non-engineered techniques in such a way, that all the necessary information is compiled in just one document, with step-by-step explanations of the various procedures of design and execution of the technique.

Lastly, it is important to note that a significant number of countries where stone masonry is still broadly practiced today, are currently not allowing the technique, or have no codes in place to begin with, such as Afghanistan, Pakistan, Bhutan, Azerbaijan, Kyrgyzstan, Morocco, Tunisia, Turkey, Yemen and Albania. For instance, in Afghanistan most of the construction takes place in rural areas and with traditional techniques. However, the Afghan building code ABC-2012 (2012) is a collection of US-based clauses that are not in line with the current engineering practices and construction needs in the country (Mashal and Sarwary, 2018). Similarly, the US-based Pakistani code (BCP-SP-07, 2007), as well as the Indian seismic code which effectively prohibits stone masonry in the whole Himalayan region (seismic zones IV and V), do not properly reflect the current needs in their respective countries.

3.9 Conclusion

Nearly 325 national seismic and masonry codes from all over the world, divided over five different continents, have been analyzed and compared. The current state-of-the-art for new rubble stone masonry buildings in seismic areas was reviewed for 57 countries in total, of which 31 in more detail. The following is concluded:

- Currently, the technique of nominally reinforced rubble stone masonry buildings with cement mortar and wooden diaphragms in seismic areas, is only allowed in seven countries in the world; Nepal, India, China, Tajikistan, Georgia, Iran and Croatia.

- No consensus was found on any of the design specifications and main dimensions between these countries and the differences vary greatly, which raises questions about the reliability and value of the knowledge in this field. A similar conclusion was drawn in Chapter 2 as well.

- The definition of the loadbearing masonry type "URM" may be perceived as misleading in earthquake engineering, as truly unreinforced masonry is not allowed in any of the codes. It is therefore proposed to internationally adopt "NRM", which stands for Nominally Reinforced Masonry, as an additional masonry category.

- The permitted use of rubble stone masonry, as well as the specifications for stone units are seldom clearly described in the codes. This can easily be improved by adding a line in the codes, which specifically states whether the technique is allowed or not.

- A further recommendation is to develop a stand-alone code for rubble stone masonry buildings, to avoid misinterpretation and interchange of incompatible design specifications that are meant for other techniques.

- Several countries where rubble stone masonry is still abundantly practiced, completely rule out the technique in their codes or have no codes in place. This is not in line with the current needs in these countries, such as in Afghanistan, Pakistan, Bhutan, Azerbaijan, Kyrgyzstan, Morocco, Tunisia, Turkey, Yemen and Albania.

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Chapter 4

Cost Analysis of Mountain Schools in Nepal: Comparison of Earthquake-Resistant Features in Rubble Stone Masonry versus Concrete Block Masonry

Summary

This chapter analyzes the cost breakdown of earthquake-resistant mountain schools in Kaski District of Nepal, as built by Smart Shelter Foundation with the techniques of rubble stone masonry and hollow concrete block masonry. The designs follow basic rules of thumb of "non-engineered seismic design", which deviate slightly from the code required provisions, as briefly explained here. The data collection took place in 2017 and the cost analyses were performed in 2018.

It is concluded that the governmental District Rates insufficiently reflect variations at the micro level, such as is the case in rural and remote locations. Therefore, a helpful tool for rapid cost estimation of different school designs is developed, which can be easily adjusted to similar contexts around the globe. It is further concluded that the inclusion of important seismic features is not very expensive, and that there is basically no financial obstacle to incorporate horizontal beams and stitches in new constructions of schools and houses.

As a side-research, a post-disaster check of possible price hikes after the 2015 Gorkha Earthquake in Nepal was carried out. The general consensus is that after a mayor disaster, the construction and material prices double, triple and even quadruple. However, no such evidence was found in the literature and neither in the cost analyses in this chapter. Actually, it was noticed that the prices of some materials such as cement had slightly decreased.

Important note: This chapter gives no indication nor opinion about which types of wall, roof or reinforcements perform better in an earthquake; the focus is purely on the implications and the differences in cost.

4.1 Introduction

Between 2007-2012 the Dutch non-for-profit organization Smart Shelter Foundation (SSF), together with local partner SEED Foundation, executed building projects in 19 villages in Kaski District of Nepal. This included the construction of 15 earthquake-resistant schools in two techniques, being locally harvested rubble stones from the mountains (Schildkamp, 2015a) and cast hollow concrete blocks (Schildkamp, 2015b). The designs were developed by SSF, following general rules of thumb from available technical literature and practical manuals. After completion of the designs, six different local Nepalese engineers were invited to make an estimate for the construction of the school buildings. Without exception, they returned a one-page estimation of the main elements, but for reinforced concrete frame buildings with columns and beams. It turned out that none of the engineers had experience with making estimates for local types of loadbearing masonry buildings with stones or blocks. Most peculiar was the fact that no difference was made between schools at different locations. Following general District Rates (DR) that apply to the whole Kaski District, the engineers prepared exactly the same estimation for 5 classrooms near Pokhara city, as for 5 classrooms in a remote

mountain village. This is not realistic, as the costs for certain materials are much higher in the mountains due to higher costs for transportation and carrying these to the site.

Therefore, SSF decided to prepare the estimates for each village themselves, based on local rates for materials, labor and transport. This has resulted in a unique collection of local building prices spanning a period of more than 10 years, which has been analyzed to provide answer to the following questions:

i) Which materials or construction phases have the biggest impact on the overall costing?
ii) Which technique is most economical; Rubble stone masonry or concrete block masonry?
iii) What are the cost implications of different solutions for foundation, walls and roofing system?
iv) Did the material and construction costs rise steeply after the 2015 Gorkha Earthquakes?
v) And most interestingly: What is the cost difference between a traditional unreinforced school building, and a fully reinforced design with the addition of seismic reinforcing features?

4.2 Literature Reviews

Prior to all analyses and calculations, a literature review on the subject of construction costs in seismically prone developing countries was carried out. The review revealed that only limited data is available, of which the majority is focusing on the costing of reinforced concrete frames, such as in India (Thiruvengadam et al, 2004) and Nepal (Subedi et al, 2016). Some literature focuses on the comparison of retrofitting solutions, such as in Bangladesh (Roy et al, 2013) and Iran (Jafarzadeh et al, 2016).

Only three references were found for unreinforced masonry (URM) with stones, bricks or blocks. For use in seismic areas, Arya (1970) explains that such constructions can be much improved by introducing vertical steel bars at corners and junctions of walls, and reinforced concrete bands at lintel level of all stories. He further states that "these provisions have been found to cost about 4 to 8 percent of the cost of buildings in areas with moderate seismic activity", although it is not mentioned for which country or region these figures apply. With regard to houses in Anatolia in Turkey, Spence and Coburn (1987) describe that "a program to encourage stronger housing construction should be aimed at both the builder, who constructs the building, and the house owner, who pays for the building. (…) The most important aspect of advocating measures to strengthen buildings is, however, the cost of doing so". For their cost comparison they make a difference between i) local materials (freely available if collected) such as stones and mud, ii) market materials (cash cost) such as concrete, brick and steel works, and iii) labor (free for local materials, paid for market materials). Transportation costs of the materials are not included. They calculate that upgrading of a medium quality traditional house costs an additional 9% for adding 1 horizontal reinforced concrete band, and that further inclusion of horizontal steel bars in the masonry joints, plus upgrading of the foundation adds a total of 28%. The third mention is made by Hausler (2004) after the 2001 Gujarat Earthquake in India, who compares the costing of a 300 square foot unreinforced brick masonry house in mud mortar, with a cement mortared brick masonry house added with horizontal bands and vertical steel reinforcements. The additional costs are +45% (from 2.67 to 3.89$/sq.ft), although numbers and dimensions of the reinforcements are not specified. However, these references are 50, 30, and 15 years old, respectively. No recent costing data was found, and neither any detailed comparisons of all the construction elements and building materials separately.

A secondary literature review was carried out to investigate the general assumption that after a big natural disaster, construction prices "shoot up" (Sustainable Safety Solutions, 2016) due to shortages of materials coupled to high demand, with reports of prices that "doubled overnight" from 25$/sq.ft to 50$/sq.ft, and then rapidly more than tripled to 80$/sq.ft (The Awkward Pose, 2012). However, hardly any literature nor data was found on this subject, besides the following limited mentions. One year after the 2004 Tsunami, construction costs per square foot for a simple house went up with 67%, from 7.74 to 12.90$/sq.ft, in Banda Aceh (Indonesia), mostly due to rising of labor and timber prices (Jayasuriya and McCawley, 2008). In Sri Lanka the increase for reconstruction of houses ranged between 30 and 50% after 8 months toward 60–80% a year later (Ruddock et al., 2010), due to hikes of material prices and shortages of labor. Interestingly, the construction costs in Thailand decreased in 2005, as the hit areas had close access to materials in Bangkok, and more importantly, because a large workforce was available due to high levels of unemployment at the time (Nidhiprabha, 2007). Regarding the post-earthquake situation in Haiti only two references were found. One organization initially reported a hike in their estimations of 131% (29$ to 67$/sq.ft) between 2010 and 2012, but this figure was revised to 86% for actually built houses (at 54$/sq.ft) in 2014 in the north-western part of Haiti (GOA-15-517, 2015), which is in line with the figures of another organization who built permanent houses at a rate of 53$/sq.ft in 2012 (GFDRR, 2016).

Shortly after the 2015 Gorkha Earthquake, immediate shortages of materials were expected in Nepal due to the heavy damage in the country. Just 3 months after the earthquake the Nepali government put a temporary ban on construction, to develop reconstruction regulations and approval guidelines. This ban was followed by a 3-month blockade of petrol, goods and materials, caused by a general political strike. As a result, increases of 40% were expected mostly for steel, sand and aggregates, but not so much for cement of which enough supply seemed available (The Himalayan Times, 2015). This is confirmed by a report of Amnesty International (2017), who documented rates of key material prices for a 2-year period and concluded that the cement prices had actually slightly decreased. They further reported that after 20 months, the price of aggregates doubled from 1,000 to 2,000 Nepali Rupee (NRS), and sand prices tripled from 500 NRS to 1,500 NRS per m^3. However, effects of these individual price hikes on the overall costing were not reported. On the national level, the predicted costs for reconstruction in Nepal were calculated based on the 2011 Census building figures (National Planning Commission, 2015a). The indicative costs per sq.ft of plinth area for cement-based masonry was increased with 25% from 1,200 NRS (10.60$) in 2011 to 1,500 NRS (13.25$) in 2015 (conversions per xe.com, December 2018). This figure is taken as a reference point for the post-earthquake cost analysis further on.

4.3 Preparing of Master Designs and Master Estimates

New sets of Master Designs were prepared of school buildings in different techniques, but all with the same dimensions to make fair comparisons between these techniques and between their separate elements. Based on these designs, Master Estimates were prepared which are divided into five main building phases, which are a) the foundation, b) walls, c) roof, d) floor and e) finishing of the building. Each phase is then further subdivided into three main cost categories, which are i) materials, ii) labor and iii) transport.

4.3.1 Master Designs

The standard designs as used for the cost comparisons are shown in **Figures 17A-F**. Although Nepal has officially adopted the Metric System (Act of 1968), most villages still use the Imperial System and therefore the drawings of **Figure 17**, as well as all units and calculations in this chapter are expressed in feet (') and inches ("), with conversions according to the SI metric system, such as meter (m) and millimeter (mm). The designs are based on the actually built projects of SSF in Nepal. These deviate slightly from the code required provisions, as explained in the previous chapters, and which will be briefly highlighted in the descriptions below:

- To make the comparisons fair, the dimensions of the classrooms for both stone as well as block designs are made similar. Both designs have an interior floor plan of 15x15ft (4.6x4.6m), which is based on the fixed dimensions of the concrete blocks. Both designs have a wall height of 8'2" (2.5m), as this corresponds with the height of 10 concrete blocks plus joints, plus the thicknesses of the necessary horizontal beams and bands.

- In general, Kaski District has firm rock soil and both designs include a foundation of 3'0" (0.9m) deep and wide, consisting of a stepped strip foundation in rubble stone masonry with cement-sand mortar, placed on a bed of stone soling with a layer of plain cement concrete, topped with a reinforced concrete plinth beam, **Figure 17E**.

- The walls are either 14" (350mm) thick rubble stone, or hollow concrete blocks with 6" (150mm) thickness, both in cement-sand mortar. Only the rubble stone walls have buttresses at all wall ends. The dimensions of the openings for both construction types also depend on the fixed size of the concrete blocks. This results in door frames of 3'2"x6'10" (0.95x2.10m) and window frames of 4'0"x4'6" (1.20x1.35m). All frames and shutters are made from a local type of hardwood named Sal.

- The walls are tied together with horizontal bands made of reinforced concrete, at five different levels in height, being foundation beam, sill band, in-between stitches, lintel beam and top beam (**Figures 17B and 17D**).

- The concrete block walls include vertical steel bars in all corners, t-sections and next to openings, in order to prevent shear cracking. However, in the thick massive rubble stone walls these vertical elements are excluded, as it is reasoned that the limited amount of steel will not provide the desired amount of ductility. Also, vertical elements may disrupt the masonry bonding in these critical connections, which possibly make these connections weaker rather than stronger. This is a mayor point where the designs deviate from the codes, and it must be noted that this remains to be a highly debated topic of discussion among experts (Schildkamp and Araki, 2019).

- Heavy masonry gables, even with a gable band, have the risk of toppling during an earthquake. To avoid this, the stone gables are replaced by wooden trusses at all interior and end walls, and then boarded up with wooden planks. Further trusses are placed at intermediate points, these are inter-connected with purlins and cross-bracing elements, and a stiff ceiling is placed underneath. This way the roof structure acts as one, thus enhancing the box action of the building. In some cases however, the villagers preferred hollow steel tubes instead of wooden truss members. These roofs have no ceiling but have steel cross-bracing in the total length of the roof and ceiling planes, and the gables are finished with tin sheets.

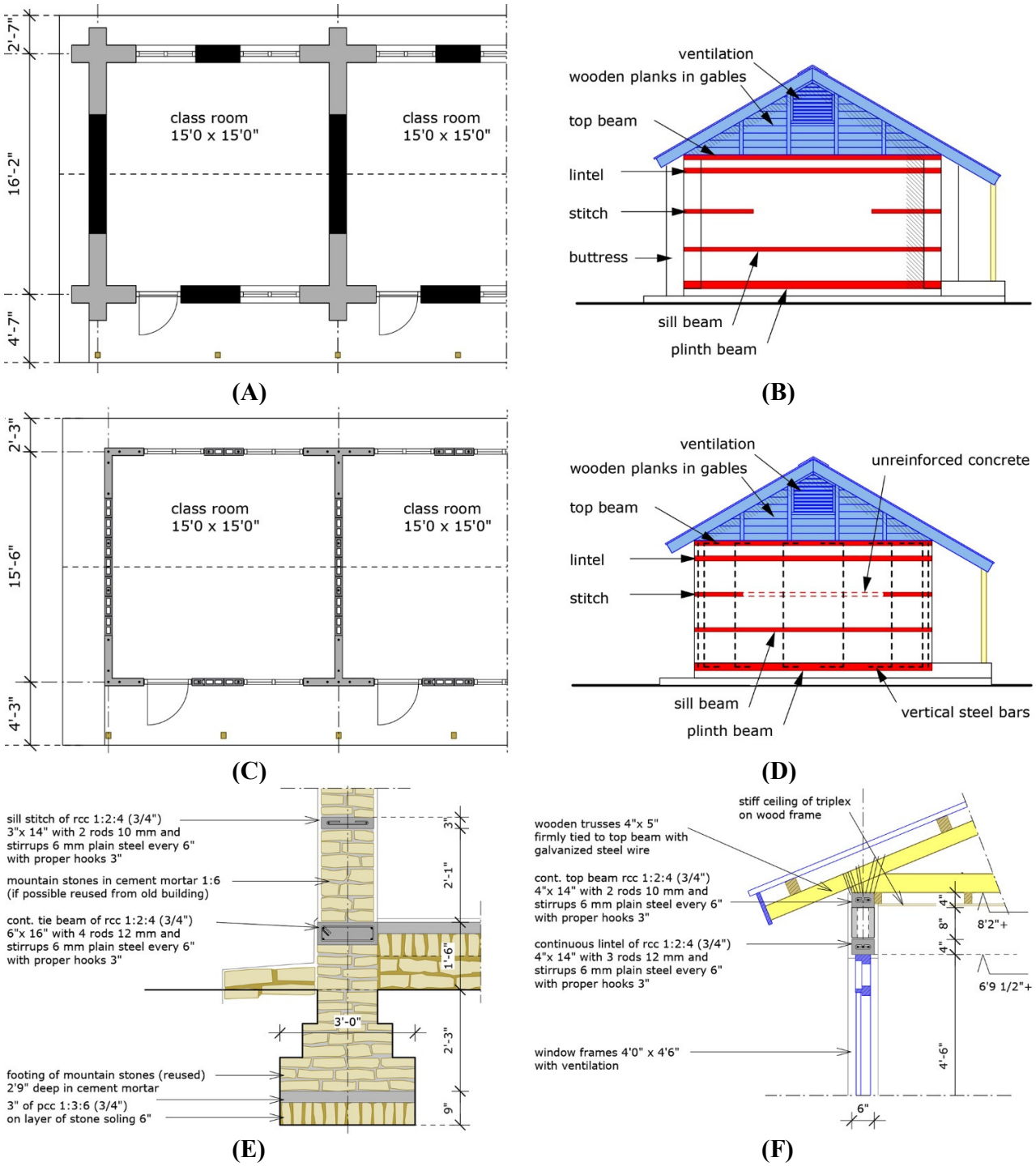


Figure 17. ***(A,B)*** *School plan and side elevation with horizontal reinforcements and buttresses, in rubble stone masonry.* ***(C,D)*** *School plan and side elevation with horizontal reinforcements and vertical steel bars, in concrete block masonry.* ***(E)*** *Detail of foundation, floor and wall in rubble stone masonry.* ***(F)*** *Detail of window, wall and roof in concrete block masonry (all figures by courtesy of Smart Shelter Foundation).*

4.3.2 Local Material Constants

Each main phase is divided into its separate building elements, for which length, area and volume are measured and calculated in feet ('), inches ("), square feet (sq.ft) or cubic feet (cft). All elements are further split into separate materials, each expressed in a certain amount or ratio, per certain unit. For instance, masonry, concretes and mortars are proportionally mixed in specified ratios of masonry material (stones, blocks) with cement, sand and/or aggregates. All these proportions are called Material Constants and can be found in tables and annexes of construction manuals such as quantity surveyor guides (Joglekar, 1997), the Indian Standard (IS:10067-1982, 2005), or the Nepali DoLIDAR Norms of the years 2063/2064 (Office of District Development Committee, 2007). This document from the Department of Local Infrastructure Development and Agricultural Roads (DoLIDAR) is often used for civil or housing project in the rural areas of Nepal and was therefore leading for the preparation of the estimates. Note that Nepal uses the Vikram Samvat calendar, which is 57 years ahead of the commonly used Gregorian calendar, meaning that the Nepali year 2063/2064 resembles the Gregorian year 2006/2007. The DoLIDAR Norms first had to be converted to the Imperial system and then further into local units, added with certain local customs, as follows:

- Locally sourced materials such as sands and aggregates are hauled from the river to the building site in old cement bags. One 50kg cement bag is equal to 1.18cft and all volumetric mixtures for mortars and concretes can be converted to numbers of bags for each material. As an example, 1m^3 of concrete mix in the ratio of 1:2:4(3/4") contains 320kg cement, 0.45m^3 rough sand and 0.85m^3 aggregates. In the mountain areas, for every 100cft (2.83m^3) this translates to 18.11 bags cement, 38.11 bags of sand and 71.95 bags of aggregates. The mixture ratio 1:2:4(3/4") means 1 volume of cement, 2 volumes of sand and 4 volumes of aggregates of 3/4 inch (roughly 20mm) in size.

- In Kaski District the mountain stones are expressed in a locally used volumetric measurement called "chhatta". The dimensions are based on a number of underarm lengths, which after long discussions with (mostly older) villagers was set at 15x4.5x4.5ft, or 303.75cft (8.6m^3). Only one reference to this unit was found in literature about forestry (Subedi et al, 2014), describing the chatta (with one "h") as a stack volume of fuelwood of 20x5x5ft, or 500cft (14.2m^3). However, SSF did not receive any negative comments or feedback on the calculations of stone quantities during or after the construction of their projects in Nepal. Therefore, 1m^3 of rubble stone masonry in 1:6 cement-sand mortar mix converts to 6.00 bags of cement, 39.83 bags of sand and 0.33 chhatta of stones, for every 100cft.

- The concrete block dimensions are 15.5"x8"x6" (395x200x150mm) and the walls are 10 blocks high. Generally, block making factories reduce the amount of cement to create competitive prices, resulting in inferior blocks everywhere. To avoid the risk of inferior weak blocks, a deal was made with a local concrete block factory near Pokhara, offering 5 Nepali Rupee (NRS) more per block if they promised to put in the correct amount of cement. The blocks for all projects were ordered here and transported into the mountains, sometimes for hours by tractor. The fact that there was minimal breakage after delivery proved that the blocks contained sufficient amounts of cement and that they were strong.

- The total needed lengths of steel bars for reinforcements are measured and then multiplied by the number of bars per beam or element, added with extra lengths for splicing, overlapping and hooks. In 2007 there was no 6mm plain steel for stirrups available in the markets, and 7mm deformed rebar was used instead. Steel quantities are expressed per kilo or per quintal (100kg).

- In the hill areas, Sal hardwood generally comes from the community forest of the villages and is therefore considered to be free of cost. Sal wood is used for the trusses and purlins in the roof, for finishing of gables and valance boards, and for door and window frames and shutters. The total price is usually calculated on just the milling fee per cft, added with transport costs to and from the mill.

- For cement, sand, aggregates and mountain stones 10% of wastage is added, for instance for spillage, mixing in wrong proportions, or drying out of a freshly mixed batch. For all wood and steel works 10% extra is added for cutting wastage, and also 10% is added to the number of concrete blocks to compensate for breakage.

4.3.3 Labor Output Constants

The amount of work turned out by labor, known as Labor Constants, are an indication of the average timing of a certain construction activity, expressed in daily or hourly wages. These constants can be divided in unskilled activities such as digging, hauling and mixing, as well as rates for skilled masons, carpenters, bar benders, steel welders and painters. According to Cartlidge (2009) the labor output is the most uncertain variable of an estimate, as it highly depends on the complexity of the project, skills of the work force, the organization of the building site and weather conditions. As a guideline the Indian Standard IS:7272-1974 (2005) was used, which covers the Indian State of Uttar Pradesh, directly neighboring Nepal. However, after execution of the first four schools in Nepal in 2007, these values were found to be too high and had to be revised, resulting in the following Labor Outputs for the Master Estimates, **Table 8**.

4.3.4 Transportation Costs

All materials that are locally harvested, such as stones from the mountains, sand and pebbles from the rivers and wood from the community forest, are basically owned by the villages and therefore regarded as free of cost. That means that the price for a cubic meter of sand or a bag of aggregates does not represent the value of the material, but this price is determined by costs for labor and transport. It includes tractor rides to the river or forest for collection of the raw materials. In case of aggregates the stones must be broken and wood must be sawn, after which it must be loaded and sent onward. The materials are transported to a drop-off point as close as possible to the construction site, from where it is offloaded, shoveled into baskets and hauled to its final destination by foot. For our estimates, it was not possible to further break down the cost of such raw materials into costs for labor and transport.

For materials that need to be purchased from outside the villages, such as cement, reinforcement steel, concrete blocks, tin sheets, paints and such, transportation fees apply. The cost of a tractor load, which usually includes loading and unloading, depends on the distance between the building shop and the village. All villages that are located near Madi River must purchase their rough construction sand from Seti River, as the Madi sand is very fine and therefore only recommended for plastering and finishing works. For these villages a higher transport rate for the construction sand is included in the estimates.

Tractors generally transport maximum loads of 2,500kg into the mountains, which roughly adds up to 50 bags of cement, or 25 quintal of steel, or 175 concrete blocks. **Figure 18** shows a schematic map of the southeastern part of Kaski District and the villages in which SSF worked between 2007-2012. It marks Prithvi Highway and the main routes (I-VI) into the hills which start from the so-called plain area, a stretch of roughly 3 kilometers between the highway and the two lakes. At some point, all routes into the hills change from tarmac to dirt roads. Distances are measured in kilometers, as well as in

number of hours by four-wheel drive vehicles (4WD), but these timings can easily double for a fully loaded tractor. The map also marks the main markets (called chowks or bazaars) and the places where to buy concrete blocks.

Table 8. *Labor Constants for work turned out by labor in Kaski District of Nepal.*

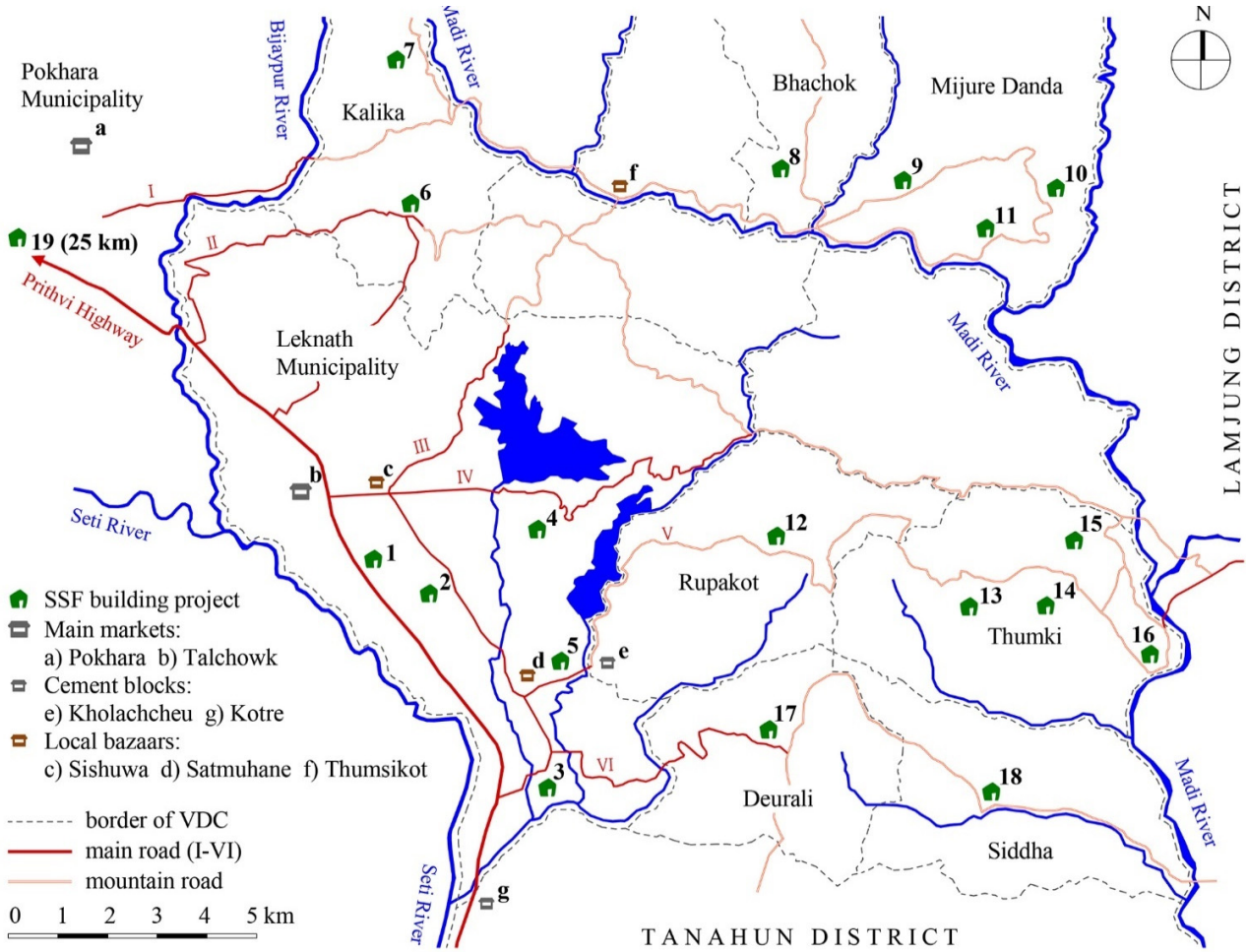
Activity	Unit	Qty per day per person (or team)	
Excavation in hard soil	cft	60.00	per laborer
Earth filling	cft	80.00	per laborer
Soling works	cft	55.00	per laborer
Plain cement concrete works (pcc)	cft	140.00	per mason
Steel bending	kg	80.00	per bender / per helper
Formwork for rcc works	sq.ft	30.00	per carpenter
Reinforced concrete works (rcc)	cft	85.00	per mason
Coursed rubble in cement mortar	cft	30.00	per mason
Random rubble in mud mortar	cft	50.00	per mason
Concrete block masonry	sq.ft	50.00	per mason
Mixing of mortar, cc and rcc works	cft	80.00	per laborer
Hauling of stones (max. 50 feet distance)	cft	160.00	per laborer
Delivery of mortar, pcc and rcc works	cft	160.00	per laborer
Making of door frames and window frames	cft	2.00	per carpenter
Making of doors and window shutters	sq.ft	5.60	per carpenter
Installing doors and windows on site	unit	3.00	per carpenter
Fixing of trusses and woodwork; per team	rooms	2.00	per 2 carpenters + 2 laborers
Fixing of roofing sheets; per team	rooms	1.00	per 2 carpenters + 2 laborers
Cutting and welding steel roof pipes; per team	rooms	1.00	per 2 carpenters + 2 laborers
Making and fixing of gable and valance boards	sq.ft	15.00	per carpenter
Fixing ceiling	sq.ft	60.00	per carpenter
Plastering works 1/2" thick	sq.ft	55.00	per mason
Plastering works 1" thick	sq.ft	70.00	per mason
Punning works (for floor finishing)	sq.ft	80.00	per mason
Cement painting (2 layers)	sq.ft	700.00	per painter
Wood painting (1 coat primer, 2 coats paint)	sq.ft	85.00	per painter

4.3.5 Collection of Local Construction Data and District Rates

Between 2007-2012 a questionnaire was filled in by all 19 villages where SSF built projects, to obtain the going prices of materials, current local wages of the laborers, and distances between the access points of the village and the nearby rivers and building shops. An example of such questionnaire is included in this thesis as Appendix A, which contains lists of requested data in both English and Nepali language. As well as an explanation of the aims of the data collection, with some examples of how to conduct the survey at village level.

For the purpose of collecting the requested data, each village established a Construction Committee, usually including the village chief, the school headmaster, some village elders and local laborers, whom after long deliberation determined all needed information. With this local building and costing data, a

final set of designs and details was prepared for each village, and a separate estimate was made, divided into the five main building phases of foundation, walls, roof, floor and finishing. To all projects 10% contingencies was added to make up for unforeseen price hikes during the construction process, for instance due to scarcity of materials or strikes in the country. Based on the estimation a financial agreement was drafted between the village and SSF. This included a certain percentage of contributions from the village called "People's Participation", as well as a payment plan of installments following a schedule of training sessions, inspections, approvals and financial reports. All these communication and administrative activities were carried out by local partner SEED Foundation.



Village name	Municipality / VDC	Chowk	in km	in time	Village name	Municipality / VDC	Chowk	in km	in time
01 Bhandardhik	Leknath Mun. (plain)	b, c	2.0	05 mins.	11 Mugribesi	Mijure Danda-5	a, b, f	26.5	3 hrs.
02 Khudi	Leknath Mun. (plain)	b, c, e	4.0	05 mins.	12 Bhirchowk	Rupakot-1	b, c, e	11.0	1.5 hrs.
03 Raja Chautara	Leknath Mun. (plain)	b, c	7.5	10 mins.	13 Thumki	Thumki-9	b, c, e	18.0	2 hrs.
04 Pachbhaiya	Leknath Mun. (plain)	b, c	5.5	10 mins.	14 Phalangkot	Thumki-2	b, c, e	20.5	2.5 hrs.
05 Kholachcheu	Rupakot-8 (plain)	b, c	7.5	00 mins.	15 Syastri	Thumki-5	b, c, e	27.5	2.5 hrs.
06 Kalikasthan	Kalika-4	a, b	11.0	45 mins.	16 Dargauntar	Thumki-1 (plain)	b, c, e	24.5	3 hrs.
07 Mahjibesi	Kalika-9	a	16.0	2 hrs.	17 Deurali	Deurali-2	b, c, g	14.5	1.5 hrs.
08 Makaikhola	Bhachok-8	a, b, f	24.0	2 hrs.	18 Khalte	Siddha-7	b, c, g	21.5	3 hrs.
09 Gahate	Mijure Danda-8	a, b, f	28.0	3 hrs.	19 Harpan	V. Tamagi-4	b, c, g	20.0	1.5 hrs.
10 Mugri	Mijure Danda-5	a, b, f	29.5	4 hrs.					

Figure 18. *Schematic map of schools and distances to markets in southeastern part of Kaski District.*

In the period between December 2017 to March 2018, a new questionnaire was distributed in the same 19 villages in order to prepare new estimates. This was done to determine if there are any similarities or deviations between the situations of 2007 and 10 years later, and to determine if any patterns exist that can be generally utilized for preparation of estimates in this district. Out of 19 surveys, 17 villages eventually returned the requested data, but this took longer than anticipated. One reason is that the roads into the mountains have improved at many places, meaning that access to the markets to buy steel tubes and concrete blocks has become easier. Therefore, some of the villages found it more difficult to determine the going rates for local materials such as wood and stones, which seemed to be less used in certain areas. Another possible reason is that there was no direct involvement in a prospective project. With this in mind, it must be noted that there may be some inaccuracies within the collected data. However, an initial review showed that on average the given prices are consistent in the different contexts (plains and hills), and therefore the recent rates are eligible for the comparisons in the next sections.

Also, the District Rates (DR) of Kaski between 2007 and 2017 were collected and separate estimates were prepared related to these DR, to detect any similarities between the actually built projects and the general trends in the whole area. Every year the DR are published right after the monsoon (around September) and these lists dictate the material rates and labor wages for the coming year. The latest versions of these rates (District Technical Office, 2015a, 2017a) can be found online, the previous versions were copied at the District Technical Office in Pokhara (District Technical Office, 2009, 2012). All DR data has been converted to the Imperial system, average transport distances between villages and chowks were determined, and estimates were prepared for each technique. These full estimations are also used for the comparisons in the next sections, and the cost distributions according to the DR are added to **Table 9** and **Figure 19.**

4.4 Comparisons of Full Estimates

To detect generalities and similarities in the overall distribution of costs, full estimates for the three types of school buildings (groups I, II, III) were analyzed and compared according to actually built rates, as well as according to the general District Rates for Kaski District. Also the effects of materials prices on the costing of separate construction elements were reviewed, such as for the roofs and the walls.

4.4.1 Eligibility Check and Grouping of Construction Types

To be included in the analyses and comparisons, first the eligibility of all projects was checked within the period 2007-2012. Estimates based on average figures of all 19 villages were prepared, and the total costs were divided over the five main construction phases being a) foundation, b) walls, c) roof, d) floor and e) finishing. These average estimates were then compared with the estimates of each individual school. Schools with phases that deviate more than 15% were deemed not eligible for the comparisons.

The eligibility check has resulted in a clear distinction of 3 groups, which are based on three different construction types. Group I is consisting of 13 villages that fall within the costing averages for rubble stone schools with a wooden roof, although only 4 villages actually decided to build with this technique

in 2008 (of which one with a steel roof). Group II includes 6 villages with concrete block schools and a hollow steel tube roof, which is the most common technique in the plain area of Leknath Municipality (**Figure 18**, no.1-5). And group III includes 10 out of 14 mountain villages that are eligible to build with concrete blocks and a wooden roof (of which 7 villages actually did so between 2007-2012). The remaining 4 (out of 14) mountain villages are the most remotely located (**Figure 18**, no.8-11) and these are the ones that actually built with rubble stone (group I). To make the comparisons fair, the same grouping was used for the period 2017, but minus the two villages that had not returned the questionnaire about local costing. Final sets of estimates were prepared based on the new averages for each group and for both time frames, and these are used for the comparisons in the next sections.

4.4.2 Distribution of Costs

When comparing the cost distribution of the main construction phases, big differences are seen between the different time frames, as shown in **Table 9** and **Figure 19**. In the period 2007-2012 the distribution for all three construction groups is similar, where both foundation and roof roughly represent a quarter of the costs, the walls around 30%, and flooring and finishing together cover the remaining 20%. Also, the ratios for materials, labor and transportation are nearly equal for all three contexts. In 2017 however, the distribution is very different for all 3 groups compared to 10 years before. For groups I and III the percentages of the foundation decreased and the roofing increased (**Figures 19A,C** versus **19E,G**), whereas for group II an increase is visible for the walls while the percentage for roofing became less (**Figure 19B** versus **19F**). Overall, the portion for the actual labor wages (**cells ii**) went up significantly in 2017, whereas the actual costs for transportation (**cells iii**) have decreased, possibly because the road networks have improved, and goods can be delivered on site.

Table 9. *Distribution of costs for main construction phases of different techniques, according to actually built rates (on the left) as well as to District Rates (on the right), at different time frames.*

Elements in %	**Rubble stone** I	**Blocks - plain** II	**Blocks - hill** III	**DR Rubble stone** I	**DR Blocks - plain** II	**DR Blocks - hill** III	**DR Blocks - hill** III	**Rubble stone** I	**Blocks - plain** II	**Blocks - hill** III	**DR Rubble stone** I	**DR Blocks - plain** II	**DD Blocks - hill** III
Year	av.	av.	av.	2008	2007	2007	2011	2017	2017	2017	2017	2017	2017
a. Foundation	25.2	23.5	23.9	22.1	23.6	21.7	16.1	20.2	23.7	19.9	16.7	21.3	15.9
b. Walls	30.9	29.2	28.3	30.3	30.3	29.3	28.2	30.7	35.4	27.7	28.9	36.1	27.6
c. Roof	23.9	26.5	26.9	29.3	24.8	29.5	40.6	31.9	18.3	34.2	39.6	22.1	41.3
d. Flooring	8.8	9.4	9.6	7.9	9.6	8.8	6.8	7.6	10.1	8.4	6.6	9.5	7.1
e. Finishing	11.2	11.5	11.3	10.4	11.7	10.7	8.3	9.6	12.5	9.8	8.2	11.0	8.2
i. Materials Total	80.3	83.0	79.1	78.0	78.9	76.6	79.7	76.3	70.9	75.9	78.7	74.5	78.4
ii. Labor Total	14.8	16.4	15.7	15.1	15.7	14.5	13.6	21.8	28.4	21.2	16.4	21.2	15.9
iii. Transport Total	4.9	0.5	5.1	6.9	5.3	8.8	6.7	2.0	0.6	2.9	4.9	4.3	5.7
	fig.A	fig.B	fig.C				fig.D	Fig.E	fig.F	fig.G		(#)	fig.H

The data also shows a big difference between the costing based on actual local rates versus the general District Rates. The DR are compared to the corresponding time frame in which the schools were actually built by SSF, which are 2008 for Group I, 2007 for group II, and 2007-2011 for Group III. In the period 2007-2008 the actual rates and District Rates are quite similar, but in the years 2011 and 2017 these differences are significant (**Figure 19D,H**). Further, a big difference is visible between the 2017 DR data for groups I and III versus the 2017 DR data of group II (marked with #), especially for the roofs. Overall, the roof portions show the largest deviations, but these charts do not indicate whether this is caused by i) a steep change in the costing of the roof phase itself, ii) by changes in other phases such as the walls or the foundation, or iii) by the increase of a certain materials, for instance Sal wood or steel tubes. These factors are further investigated in the next sections.

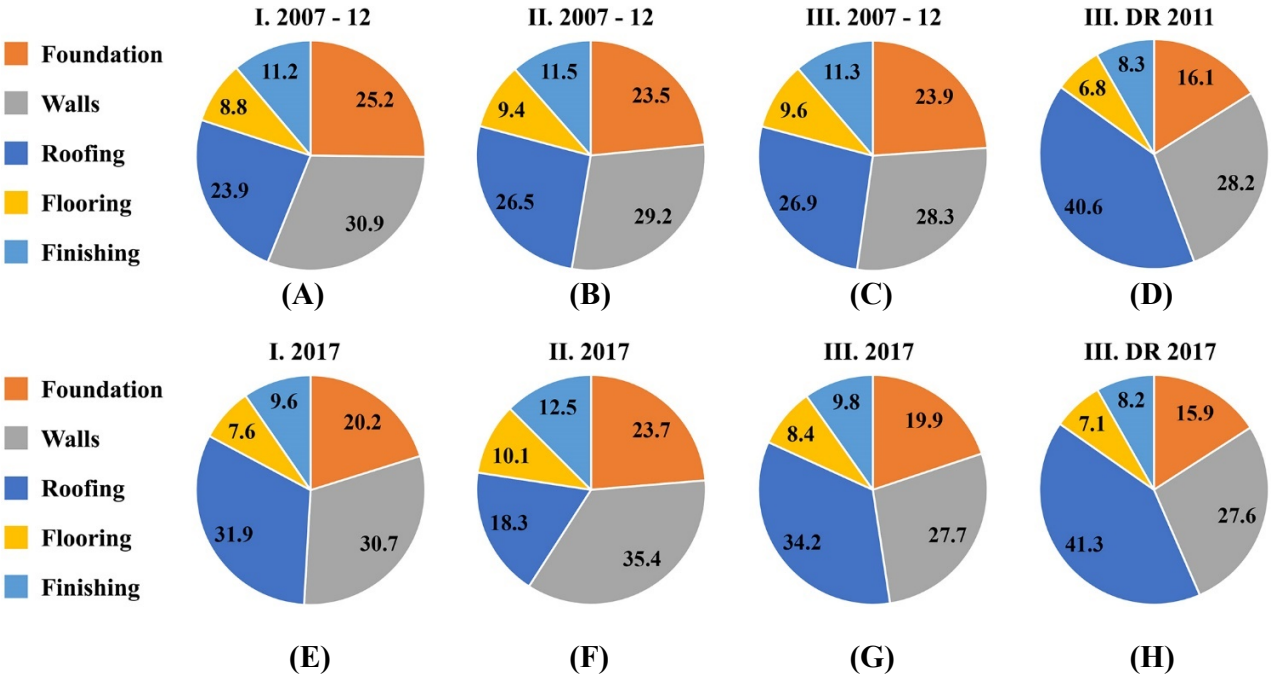


Figure 19. *Cost distribution of main construction phases in different time frames for: (A,E) Group I, rubble stone in the hill areas; (B,F) Group II, cement blocks with steel roof in the plain areas; (C,D,G,H) Group III, cement blocks with wooden roof in the hill areas.*

4.4.3 Comparison of Material Rates and Labor Wages

This section reviews which materials or costs have the biggest impact on the overall costing of a construction project in Kaski District of Nepal. **Figure 20** shows the fluctuation of material prices and labor wages according to the District Rates between 2007 and 2017. The charts indicate that prices of stones (+124.3%) and sands (+117.9%) have more than doubled in the last 10 years, with a large peak in 2010. This differs from the situation in Dholaka District, where these prices were reported to have doubled and even tripled in just 20 months between 2015 and 2017 (Amnesty International, 2017). A bag of cement on average increased between 0-10% each year, but in total went up with only 34.2%, from 585 Nepali Rupee (NRS) in 2007 to 785 NRS in 2017. The price of tin sheets has not changed at all in 9 years, and even went down in 2017 with -2.3%. Reinforcement steel (here expressed at cost per kg) fluctuated slightly, with a big hike in 2008 following global trends, but the 2017 rates are also lower than 2007, with -0.77%.

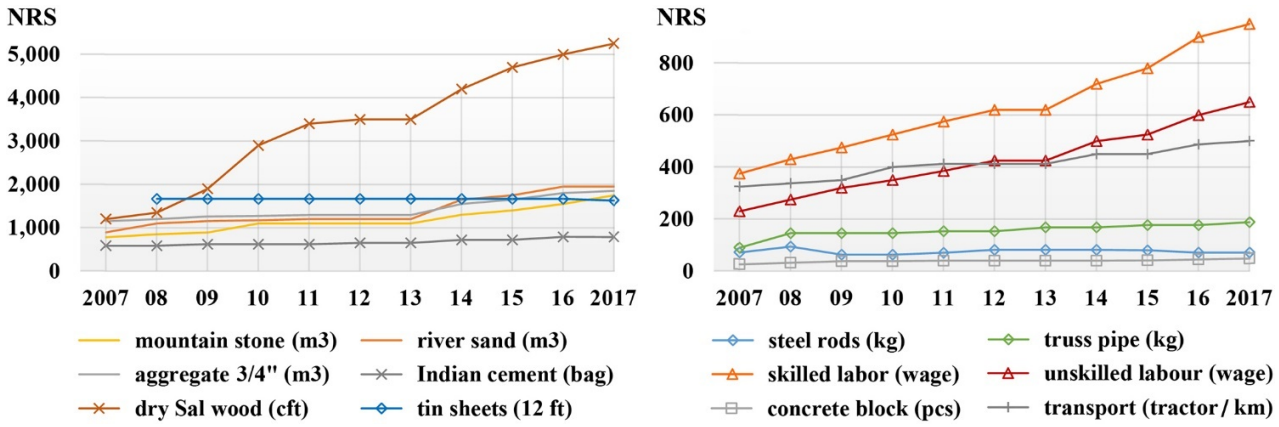


Figure 20. *Increase of main material prices, wages and transportation cost between 2007 and 2017, according to the District Rates in Kaski.*

On a positive note, the wages for labor have steadily increased between 7-15% each year. For skilled work the wages were raised from 375 NRS to 950 NRS (+153.3%). Unskilled labor went up even more, with an increase between 10-20% per year, and almost tripled from 230 to 650 NRS (+182.6%). This also explains the large increase for the price of mountain stones, as it is very labor-intensive to hack, haul and transport new stones from the mountains. The unit that really stands out is the price of 1 cubic foot of sawn and dried Sal wood, which spiked the most of all materials with over 40% increase in 2009 and another 52.6% in 2010. The price then stabilized for 2 years and gradually rose further to a total increase of +337.5%, from 1200 NRS in 2007 to 5250 NRS in 2017. The competing truss material of hollow steel pipes (in kg) increased much less, as these prices "merely" doubled in 10 years with 108.9%, from 90 NRS to 188 NRS.

Table 10. *Price differences of main materials between local village rates and District Rates for actually built schools of group III, in 2007 and 2011, and differences according to 2017 rates; all in NRS.*

Materials	**Unit**	III.2007	DR.2007	%	III.2011	DR.2011	%	III.2017	DR.2017	%
mountain stone	cft	17.80	22.09	24.1	9.88	31.14	215.3	76.69	49.55	-35.4
soling stone	cft	14.74	22.09	49.9	9.88	31.14	215.3	48.37	49.55	2.4
river sand	bag	48.10	29.90	-37.8	76.50	40.08	-47.6	65.00	66.30	2.0
aggregates	bag	58.60	38.41	-34.5	85.50	43.25	-49.4	61.50	61.79	0.5
cement	bag	465.00	585.00	25.8	580.00	620.00	6.9	926.25	785.00	-15.2
concrete block	block	20.00	26.00	30.0	35.00	39.90	14.0	55.00	48.00	-12.7
steel rods	kg	58.00	71.65	23.5	80.50	70.45	-12.5	86.50	71.10	-17.8
tin sheets	bundle	7,300.00	9,995.00	36.9	9,000.00	9,995.00	11.1	11,040.63	9,770.00	-11.5
Sal wood	cft	375.00	1,200.00	220.0	1,105.00	3,400.00	207.7	3,437.50	5,250.00	52.7
skilled labor	day	250.00	375.00	50.0	575.00	575.00	0.0	831.25	650.00	-21.8
unskilled labor	day	193.75	230.00	18.7	400.00	385.00	-3.8	1,112.50	950.00	-14.6

The general DR prices were cross-checked with the going rates as obtained from the villages. This was done for the actually built schools with concrete blocks and wooden trusses (group III) for the years 2007 (4 schools) and 2011 (2 schools), as well as for the average village rates of 2017. **Table 10** clearly indicates that there is no similarity between the two rate systems, as the rates fluctuate heavily and with large differences. This is mostly the case for the mountain stones, cement and steel, as well as for the

skilled and unskilled labor wages. For instance, the differences per cft of mountain stones range from +215.3% in 2011 to -35.4% in 2017. Overall, the table shows that in 2007 the DR were significantly higher than the local rates, but that this situation has completely reversed in 2017 with the only exception of Sal wood.

4.4.4 Comparisons of Total Amounts

The differences between the actual village rates and the general District Rates are most clearly visible when comparing the total amounts of fully constructed school buildings. To show this, the total estimated amounts according to local village rates were compared with the total estimated amount according to the DR, of the corresponding years that SSF built a school in those particular villages (these are marked with *). **Table 11** shows that for 14 out of 19 schools, the estimates made with the DR are much higher compared to the village rates, with percentages between +32.5% to +49.0%. It is noted that all these 14 projects are located in the hilly regions. In 2017 however, these differences have become less, especially for the projects in the plain areas that are built with blocks and steel roof (no. 01-05 of **Figure 18**), with differences ranging between -3.3% and +4.2%. Compared to the plain area, the DR are a lot higher for the remote villages that built with rubble stone, with the highest difference in Mugri (+37.4%).

Table 11. *Comparison of total amounts and amount per square foot, between actual rates and District Rates in different time frames, all in Nepali Rupee (NRS).*

Village	Year	Wall / Roof	Local	D.R.	%	local 2017	D.R.2017	%
01 Bhandardhik	2007-08	blocks / steel	722,756	794,482	9.9	1,576,658	1,524,212	-3.3
02 Khudi	2007-08	blocks / steel	651,135	794,482	22.0	1,556,644	1,524,212	-2.1
03 Raja Chautara *	2007-08	blocks / steel	574,089	794,482	38.4	1,499,047	1,524,212	1.7
04 Pachbhaiya	2007-08	blocks / steel	760,804	794,482	4.4	1,462,131	1,524,212	4.2
05 Kholachcheu	2007-08	blocks / steel	556,770	794,482	42.7	1,508,135	1,524,212	1.1
06 Kalikasthan	2007-08	blocks / steel	838,319	794,482	-5.2	1,534,680	1,524,212	-0.7
Average NRS/sq.ft	2007-08	blocks / steel	763	1,056	**38.4**	2,025	2,027	**0.1**
12 Bhirchowk *	2007-08	blocks / wood	615,777	898,892	46.0	2,277,726	2,118,305	-7.0
13 Thumki *	2007-08	blocks / wood	678,400	898,892	32.5	1,876,741	2,118,305	12.9
14 Phalangkot *	2007-08	blocks / wood	675,384	898,892	33.1	2,036,674	2,118,305	4.0
15 Syastri *	2007-08	blocks / wood	628,435	898,892	43.0	1,986,016	2,118,305	6.7
Average NRS/sq.ft	2007-08	blocks / wood	864	1,195	**38.3**			
07 Mahjibesi *	2008-09	blocks / wood	711,304	1,032,045	45.1	1,921,519	2,118,305	10.2
17 Deurali *	2008-09	blocks / wood	724,131	1,032,045	42.5	1,768,731	2,118,305	19.8
Average NRS/sq.ft	2008-09	blocks / wood	954	1,372	**43.8**			
16 Dargauntar *	2011-12	blocks / wood	1,055,184	1,497,010	41.9	1,766,562	2,118,305	19.9
18 Khalte *	2011-12	blocks / wood	1,004,634	1,497,010	49.0	1,794,211	2,118,305	18.1
Average NRS/sq.ft	2011-12	blocks / wood	1,370	1,991	**45.3**	2,565	2,817	**9.8**
08 Makaikhola *	2008-09	rubble / wood	841,139	1,157,987	37.7	2,257,281	2,379,136	5.4
09 Gahate *	2008-09	rubble / wood	860,506	1,157,987	34.6	1,949,250	2,379,136	22.1
10 Mugri *	2008-09	rubble / wood	873,863	1,157,987	32.5	1,732,168	2,379,136	37.4
11 Mugribesi *	2008-09	rubble / wood	779,390	1,157,987	48.6	2,086,542	2,379,136	14.0
19 Harpan	2008-09	rubble / wood	1,208,283	1,157,987	-4.2			
Average NRS/sq.ft	2008-09	rubble / wood	956	1,320	**38.1**	2,287	2,712	**18.6**

Notes: Schools marked with * are actually built in the mentioned technique.
The **bold** numbers mark the average differences between local and district rates.

Further, the average amounts in NRS per square foot were calculated. The plinth area of the rubble stone schools (floor plan minus open veranda and aprons) is 877sq.ft versus 752sq.ft for the concrete block schools. In the period 2007-2012 the average D.R. rates per sq.ft are much higher than the local rates, between +38.1% to +45.3% for the actually built schools (marked with *). For 2017 the averages were taken for all villages, and now the differences are less, with an almost equal price per sq.ft in the plain area (only +0.1%), and differences between +9.8% and +18.6% in the hills. Overall, **Table 11** indicates that in 2017 it is cheapest to build in the plains with blocks and steel roof, at an average rate of 2,025 NRS/sq.ft, and that the price in the remotely located villages is lower (2,712 NRS/sq.ft) than in the overall hill regions (2,817 NRS/sq.ft). A possible explanation is that these remote villages have better access to stones and wood. With that in mind it is interesting to notice the large cost differences between villages that have built with the same techniques. Even though some of these villages are located next to each other (for instance nos. 8-11), the situation at micro level often differs in such way that it creates a high impact on the overall costing. Therefore, the effects of local cost influences are further reviewed in the next sections. Lastly, it is noted that the average amount per square foot in 2017 is much higher than the predicted governmental rates in 2015, which were then set at 1,500 NRS/sq.ft for cement-mortared masonry.

4.4.5 Comparison of Different Roofing Systems

Important note: The following two sections about the roof and the walls gives no indication nor opinion about which roof type performs better in an earthquake; only about the differences in cost. As seen in **Table 9** and **Figure 19**, the roof portions show the largest deviations in the cost distribution. To investigate possible causes, a comparison was made for the roof structure itself according to local village rates. Steel trussed roofs made with round hollow pipes are compared to wooden trusses that are made from locally harvested Sal wood. Due to the thicker rubble stone walls, these buildings and its roofs are slightly longer and wider, with a surface area of 1,453sq.ft for rubble stone schools versus 1,310sq.ft for concrete block schools. The first comparison shows that between 2007-2012 the truss material of steel pipes is much more expensive in the mountains than Sal wood roofing members, with prices more than double for Group I and nearly double for group III (**Table 12A**). This situation has completely changed in 2017, where wood has become three times more expensive than steel tubes, for all three groups.

However, we cannot draw conclusions from the average costing of one single material alone. Therefore, a second comparison was made for completely finished roof types at different locations. Estimates were prepared for representative villages in both wood and steel, where (*) marks the type of roof that was actually built (**Table 12B**). Although the dimensions for the roof are the same for Group II and III (both have walls in concrete blocks), the detailing is different. The wooden roofs at group III consume a higher quantity of wood for closing up the gables, for finishing with valance boards and for installation of a stiff wooden ceiling. Whereas at the steel roofs of group II, the gables are closed up with tin sheets instead, and the wooden ceiling is replaced by steel bracing. To emphasize the difference between the main materials wood and steel, the tin sheets on top of the roof are left out of the calculation.

Table 12B shows that between 2007-2012 a fully wooden roof was cheaper for groups I and III (hills), but more expensive for group II (plains). Interestingly, three villages have deviated from this which are marked with (*[!]) and for one case the reason is known to the authors: Since the village of Makaikhola does not own a community forest, they have to to buy woods from other villages. Even

though they had quoted the going rates at the time, they were unable to obtain the wood for a good price and chose to go with steel tubes instead. Why Bhirchowk and Kalikasthan decided to deviate is unknown, possible reasons are scarcity of wood, local preference, village politics, unawareness of higher steel price, etcetera. The table further indicates that already in 2011 a shift is noticed from wood to steel in the hills (Dargauntar is located in a plain area which is situated within the hilly region) due to the rapidly increasing wood prices. And in 2017 it is very clear that steel roofs have become the cheapest option for all three contexts. Feedback from Mr. Damodar Bhakta Thapa of SEED Foundation confirms that indeed these days (2017-2018) most villages choose steel roofs over wooden roofs, simply for financial reasons.

Table 12. *Cost difference in % of different solutions for the roofing and walling systems, according to village rates prices in Nepali Rupee (NRS).*

	2007-2012	**2007-2012**		**2017**	**2017**	
5A. Truss Types in NRS	**Steel Truss**	**Wood Truss**	%	**Steel Truss**	**Wood Truss**	%
Group I, rubble	108,893	49,413	-54.6	119,636	354,856	196.6
Group II, blocks-plain	70,169	86,828	23.7	113,442	401,284	253.7
Group III, blocks-hills	95,207	56,410	-40.8	109,912	333,825	203.7
5B. Roof Structure in NRS	**Steel Roof**	**Wood Roof**	%	**Steel Roof**	**Wood Roof**	%
Group I, Mugribesi (2008)	156,428	* 99,438	-36.4	163,472	507,687	210.6
Group I, Makaikhola (2008)	*! 157,839	100,023	-36.6	165,765	805,888	386.2
Group II, Raja Chautara (2007)	* 95,824	164,723	71.9	153,044	564,067	268.6
Group II, Kalikasthan (2007)	*! 153,248	112,003	-26.9	169,599	677,091	299.2
Group III, Bhirchowk (2007)	*! 111,248	96,094	-13.6	139,902	687,343	391.3
Group III, Mahjibesi (2008)	177,317	* 118,937	-49.1	167,499	618,017	269.0
Group III, Dargauntar (2011)	144,174	*! 245,571	70.3	158,922	467,018	193.9
5C. Walls in NRS / sq.ft	**Rubble stone**	**Blocks**	%	**Rubble stone**	**Blocks**	%
Group I, masonry only	12.41	10.91	-12.1	28.80	19.03	-33.9
Group II, masonry only	10.39	6.70	-35.5	28.20	15.32	-45.7
Group III, masonry only	12.84	10.54	-17.9	29.57	18.89	-36.1
5D. Total project cost in NRS	**Rubble stone**	**Blocks**	%	**Rubble stone**	**Blocks**	%
Group I, Mugribesi (2008)	*! 779,390	771,070	-1.1	2,082,571	1,788,690	-14.1
Group II, Raja Chautara (2007)	754,589	* 574,089	-23.9	2,177,667	1,900,663	-12.7
Group III, Mahjibesi (2008)	773,262	* 711,304	-8.0	2,162,717	1,912,704	-11.6

Notes: * marks the type of roof or wall material that was actually used in the village.
The villages marked with *! have chosen for the more expensive option.

4.4.6 Rubble Stone Masonry versus Hollow Concrete Block Masonry

Also, the effect of different wall types was compared and added to **Table 4.5**. For all three groups I, II and III, the price is analyzed for a unit of rubble stone masonry of 14" (350mm) thickness and a unit of concrete block masonry of 6" (150mm) thick, including costs for labor and transportation. It is interesting to note that bricks have never been popular in the Pokhara region due to high transportation costs, as good quality bricks are almost solely produced in Kathmandu Valley. To make the comparison most realistic, a unit wall surface of 100sq.ft was taken, so that vertical reinforcements were included in the calculations as well. For the block walls this means the insertion of 4 steel rods, plus grouting in the block cavities around the steel bars. The rubble stone wall specimen with dimension of 10x10ft includes one buttress. This was then divided by 100 to determine the amount in NRS per square foot,

and the cost differences are presented in **Table 12C**, showing that a square foot of block masonry already was cheaper around 2007, and over time has become even more cheaper than rubble stone masonry.

However, these figures are based on averages, and only part of the wall system is considered. Therefore, the estimates of fully completed projects in both blocks and stones were compared. Of each group the village with the largest difference was selected (**Table 12D**), whereas (*) marks the technique in which the school was actually built in that village. This table indicates that in the period 2007-2012, construction with concrete blocks was cheaper than construction with rubble stone in all cases. Although the differences for group I are minimal, ranging between -6.0% in Makaikhola (not in table) and -1.1% in Mugribesi. In 2017 the difference is more obvious and concrete blocks have become significantly cheaper than rubble stones, for all groups. In the plain areas (group II), concrete blocks have already been the first choice of masonry material for a long time. If the road networks continue to improve and if the cost difference between stones and blocks further increases, it is expected that concrete blocks will become the main choice for wall material in the hills and possibly for the mountain areas as well. As with the roofing system, it must be clearly noted that this section gives no indication nor opinion about which wall type performs better during a seismic event.

4.4.7 Impact of Local Factors

The previous sections indicate that some villages have chosen for a more expensive solution, such as a wooden roof over a steel roofing system, or mountain stones over cement blocks. The choice depends not only on local availability, but also on preference. So does this mean that the remote villages make a wrong choice in opting for the slightly more expensive mountain stones ten years ago? Not necessarily, as in reality the difference may have been less than the figures show. To build with blocks, specially trained masons must be hired from Leknath area, and there the labor wages are higher. Besides, during those years the whole country of Nepal was subjected to massive electricity and petrol shortages, creating shortages of cement and machine-made products such as hollow concrete blocks, as well as transportation problems of materials into the hills and mountains (Housing Nepal, 2009). Another reason to choose rubble stone over blocks may simply have been that the villagers are more accustomed to the traditional technique with stones. As a positive side effect, the use of locally available materials stimulates the local economy and provides jobs within the village, rather than hiring people from outside. Such local restrictions and preferences have likely played a more important role in the selection of a particular technique, and such factors will vary from village to village.

From the above comparisons it can also be derived that the District Rates do not represent the actual cost situation in the villages. A logical explanation is that the DR are general figures that apply to the whole district, while Kaski District includes 6 different altitude levels between 350m (plains with tropical climate) to 8,091m (trans-Himalayan with arctic climate), with populations ranging from Metropolitan city level to extremely remote and sparsely habited settlements (Central Bureau of Statistics, 2014). Local influences such as availability of materials and accessibility to the site, as well as local customs and preferences, have a high impact on the costing at village level. Such local factors however are not reflected in the general rates which are more representative for trends and fluctuations of national and global market prices. To address the impact of factors at the micro level, the following chapter includes a solution for comparison of different techniques according to the local situation in the villages.

4.4.8 Post-Earthquake Increase of Construction Costs

SSF only possesses actual and local construction data for the year 2017, and it was therefore not possible to analyze the post-earthquake trends since 2015 in Kaski District. An attempt was made to obtain post-disaster costing data from the 14 districts that are marked as "severely or crisis-hit" (National Planning Commission, 2015b), through a short survey in 2018 among 450 post-disaster relief workers and through the coordinating organization Global Shelter Cluster Nepal. This unfortunately did not receive much response, nor any useful data to construct a clear view on the fluctuation or increase of prices between 2015 and present times. Therefore, it was only possible to compare the general trends of the District Rates of Kaski vs. the DR of Gorkha (District Technical Office, 2015b, 2017b), the latter being the district where the 2015 earthquakes took place, which is marked as "crisis hit".

Figure 21A shows the cost of several main materials between 2013 and 2017. Generally, wood is more expensive in Kaski, whereas sand and aggregates are more expensive in Gorkha. In Kaski (dotted lines) the price of sand rose from 1,750 NRS in 2015 to 1,950 NRS in 2017 (+11.4%), and aggregates increased +25.0%. In Gorkha these numbers are completely different with no price difference for sand at all, and a surprising decrease of −27.6% for aggregates. It is interesting to note that these prices increased the year before the earthquake, and not after. To evaluate the increase of total costs, **Figure 21B** shows the absolute amount per square foot of plinth area, for 10 years of building data from Kaski, and 5 years from Gorkha, calculated for all three techniques. Between 2013 and 2017 the yearly increase in Kaski ranges between 7 and 10% on average, and in Gorkha between 5 and 7%. More striking deviations were seen in Kaski in 2008, caused by a spike of global market steel prices (Reuters, 2008), another one around 2010, and a big rise in 2014 (Housing Nepal, 2014), which is the year before the earthquake.

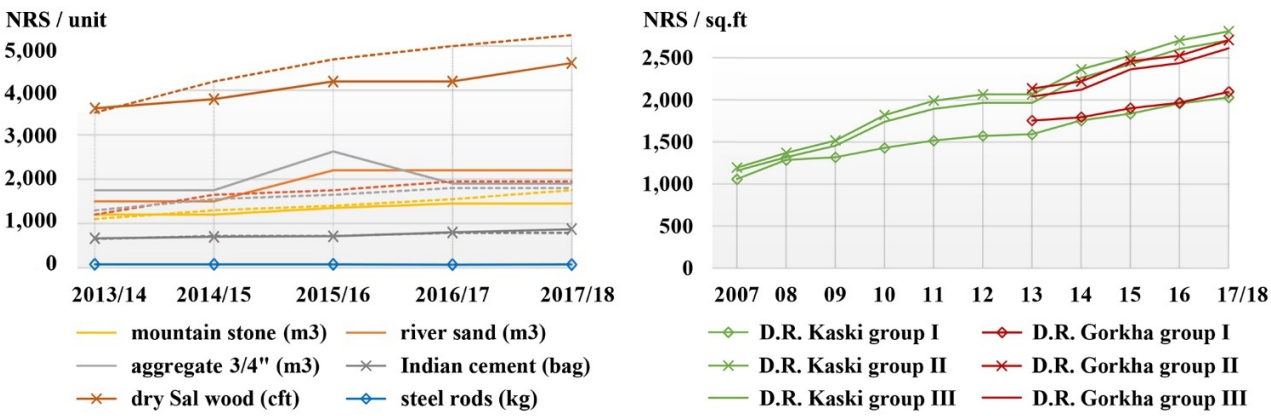


Figure 21. (A) *Increase of main material prices, wages, and transportation cost between 2013 and 2017 in Gorkha District (and dotted lines for Kaski District).* ***(B)*** *Increase of amounts per square foot in Kaski and Gorkha Districts.*

Even though the District Rates may not reflect the actual situation at village level, overall, there are no indications of doubling or tripling of separate material or total construction costs after 2015. The highest increase of a single material in Kaski is for mountain stones (+25.0%), and in Gorkha for cement (+22.5%). This is in sharp contrast with the (only) report that was found (Amnesty International, 2017), where aggregate prices increased with +100% and sand with +200% in just 20

months. In Kaski it took nearly 10 years for these prices to double. It is hoped that the NGO's involved in reconstruction have documented and are willing to share the pricing of materials, so that an in-depth post-disaster cost analysis can be carried out at the national level. However, at the writing of this thesis in 2021, no additional post-reconstruction costing data was found or obtained.

4.5 Cost Comparisons of Seismic Features

This section focuses particularly on the costing of seismic reinforcing elements in rubble stone schools with a wooden roof (group I), and on cement block schools with a steel roof (group II). The price implications of adding or removing certain seismic features, such as better-quality mortars, horizontal bands and/or vertical reinforcements is reviewed according to the local village rates of 2017. Again, it is emphasized that this section gives no indication nor opinion about which construction type performs better during a seismic event. A step-by-step cost overview is added, where a traditional unreinforced school is seismically improved, strengthened and fully reinforced. This includes the addition of all non-structural elements such as flooring and finishing, to provide the total cost and cost distribution for a fully finished earthquake-resistant school construction project. To make all information useful and applicable for the reader, the section ends with a solution for rapid cost estimation of different school designs.

4.5.1 Types of Mortar in Rubble Stone Masonry

The first comparison looks at the costing of different mortar types in rubble stone masonry, which is used for the foundation at all three groups, and for the walls at group I only. For the foundation, there is no clear answer in the literature which mortar type is best below ground level and therefore the following recommendations are based on personal experience of Smart Shelter Foundation. Mud mortar is the main choice in the villages but is not recommended by SSF. This type has the risk that the mud washes out from the joints during the monsoon season. A possible alternative is stabilized mud mortar, by adding 10% cement to the mortar mix, but this type is also not recommended by SSF, as there is insufficient data available about the effect of adding stabilizers to the Nepali mountain soils. The use of lime-based mortars is uncommon in the hills and mountains of Nepal and therefore SSF builds their foundations with cement-sand mortar in the mixture ratio 1:6.

Table 13A shows the price difference between mud mortar and cement-based mortar per 100 sq.ft of stone masonry of 14" (350mm) thickness, including costs for materials, labor and transportation. In group II the price of cement is less and the price of mud is higher compared to the hills and mountains, which results in a (expected) percentual difference between the two areas. It is however important to realize that stone masonry with cement mortar is much stronger than stone masonry with mud, as well as to recognize that the price increase of stones is of more influence on the total costing than the price of the mortar, as seen in **Table 10** and **Figure 20**.

Table 10 also indicates that soling stones, such as round boulders from the river, are cheaper than mountain stones. Therefore, the costing of a full stepped strip foundation in mountain stones is added to **Table 13A**, including costs for digging the trenches, placement of stone soling with a top layer of plain cement concrete (pcc) in the bottom, and stone masonry in cement mortar above ground level. This type is then compared to a monolithic cast strip foundation called a “plum foundation”, or

"cyclopean concrete foundation", which consists of 50% boulders of maximum 10" (250 mm) dimension in a plain concrete mixture of 1:3:6(3/4"). **Table 13A** shows that cost savings are possible between 30-40% for both groups, but with two notes. Firstly, the behavior of this type of foundation subjected to seismic loading must be validated. And secondly, for walls this technique is not suitable since it needs specialized formwork, scaffolding and highly trained workmanship, which is generally not available in the mountains; if technically possible to begin with.

Table 13. *Cost difference for different solutions for (A) the foundation, and (B) horizontal reinforcements in the walls, as per 2017 local village rates in Nepali Rupee (NRS).*

	Group I					**Group II**				
A. Masonry	**Mud**	**C-S 1:6**	**%**	**Plum**	**%**	**Mud**	**C-S 1:6**	**%**	**Plum**	**%**
per 100 sq.ft	12,600	22,040	74.9	14,729	-33.2	13,878	21,591	55.6	12,298	-43.0
strip foundation	220,449	297,078	34.8	206,495	-30.5	223,748	286,370	28.0	174,208	-39.2
B. Hor. Bands	**5 levels**	**4 levels**	**%**	**3 levels**	**%**	**5 levels**	**4 levels**	**%**	**3 levels**	**%**
total amount	2,162,150	2,130,624	-1.5	2,119,707	-2.0	1,520,523	1,469,051	-3.4	1,478,287	-2.8

4.5.2 Horizontal Seismic Reinforcements

The second comparison analyzes the cost differences for removing horizontal seismic reinforcing elements. It must be clearly noted that these effects are examined from a financial viewpoint only. Smart Shelter Foundation built their schools with horizontal reinforcements at 5 levels, being from bottom to top: 1) plinth beam at foundation level; 2) sill beam under the windows; 3) in-between stitches in corners and t-sections; 4) lintel over all openings; and 5) top beam at roof level (**Figure 22A**). When reducing the number of reinforcements from 5 to 4 levels, there are three options: i) keep the sill band and remove the in-between stitches; ii) combine the sill band with the stitches at the same level; or iii) remove sill band and keep just the stitches. The choice is made for the third option (**Figure 22B**), as for this case the cost saving is most favorable. A further reduction of horizontal reinforcements can be achieved by combining lintel and top beam, again with the placement of stitches (option iii) halfway the wall height (**Figure 22C**).

The cost differences of removing one or two levels of reinforcements are shown in **Table 13B**, which indicates that the difference is 2.0% at best for group I for a completely built school. This relatively modest cost reduction in rubble stone buildings is caused by two things. Firstly, as the top level of the walls is fixed, the door and window frames become slightly higher for which the extra costs are adjusted in the estimates. Secondly, stitches are easily incorporated in rubble stone masonry, but when a beam is removed, this part is replaced by stone masonry which is a costly element in 2017. Also, with the concrete block walls in group II a few remarkable things happen (**Figure 22D**). Sections of unreinforced concrete bands are cast between the reinforced stitches to avoid cutting of all blocks over the full length of the building. And an important consequence of removing beams is that the ceiling level becomes too low, and therefore an extra row of blocks must be added to the wall height. Due to these additions in the walls (shown in orange), together with extra wood for the higher door and window frames, the reduction from 4 to 3 bands is actually more expensive than removing only one reinforcement from 5 to 4 levels.

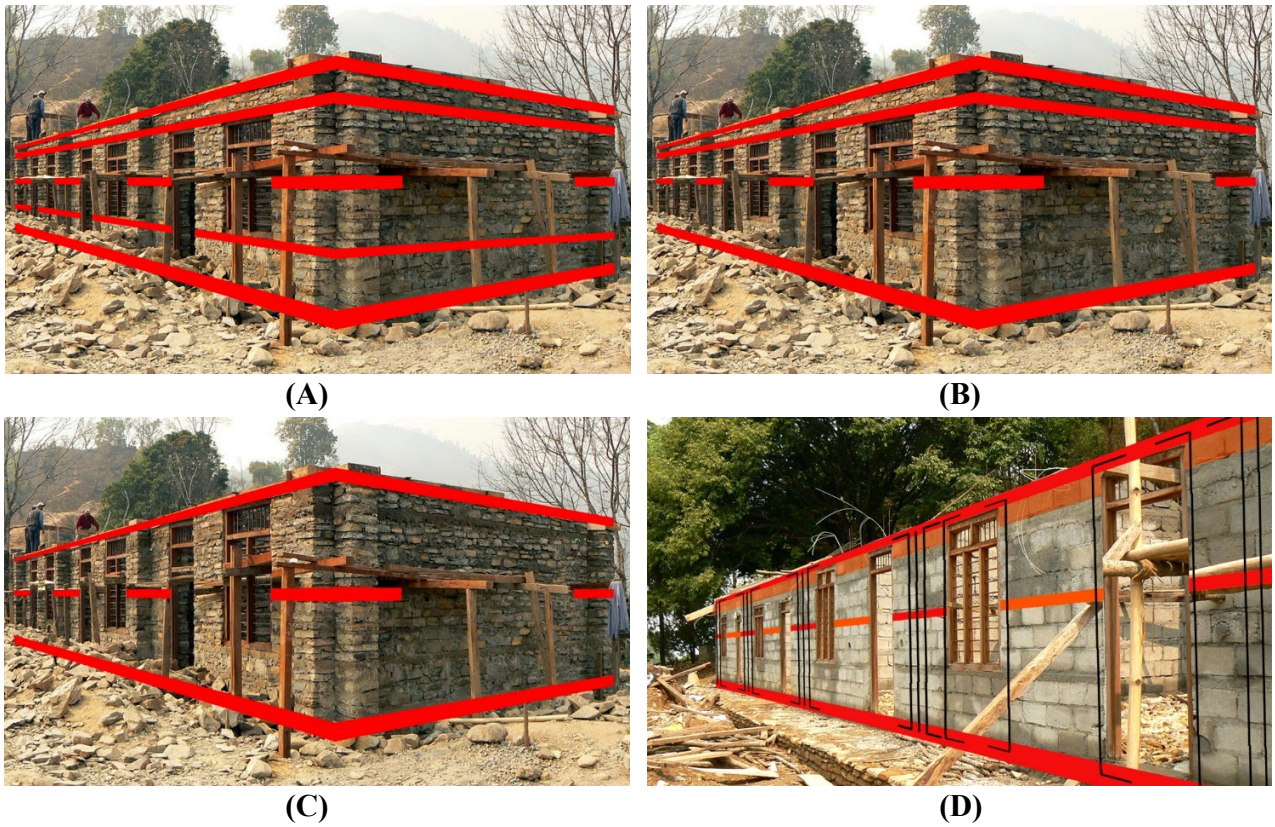


Figure 22. *Horizontal reinforcements in rubble stone masonry walls, at:* ***(A)*** *5 levels;* ***(B)*** *4 levels;* ***(C)*** *3 levels; and* ***(D)*** *Horizontal beams in concrete block masonry at 3 levels (all by courtesy of Smart Shelter Research).*

Overall, in the very best case a cost reduction is achieved of 42,443 NRS in the hills (group I) and 42,236 NRS in the plain areas (group II), which roughly translates to 375 US$ for each case (xe.com, December 2018 at the time of the research, as well as xe.com, Februrary 2021 at the moment of writing this thesis). This may seem as a very minimal cost saving, but this amount covers 2 full beams in a design of 3 classrooms, which translates to roughly 62 US$ per band per room. This is actually a very important and positive outcome, as it means that the inclusion of these important seismic features is not that expensive, and that there is basically no financial obstacle to incorporate horizontal beams and stitches in new constructions of schools and houses.

4.5.3 From Unreinforced to Fully Reinforced Rubble Stone Masonry

To further analyze the cost implications of adding seismic features to the school designs, the construction sequence is simulated of transforming a traditional non-reinforced building into a fully reinforced school. A set of drawings of a traditional unreinforced school building was prepared, based on pictures of rubble stone buildings that were taken all over Kaski District between 2006 and 2018, such as **Figure 23A**. It was especially this type of construction that suffered the most damage in the 2015 Gorkha Earthquakes. Although official numbers have still not been released by the Nepali government (as of February 2021), it is estimated that nearly 1,000,000 houses and 57,000 classrooms were destroyed and damaged throughout the country (The Post Disaster Recovery Framework, 2016). It is further estimated that 81% of all building damage took place in the rural areas, where 95% of all

collapsed structures consisted of low-strength masonry; the majority being stone with mud mortar (National Planning Commission, 2015a). The unreinforced design has similar dimensions as the Master sets and is gradually improved as described below. Of each step the cost implications are shown in **Table 14A**, resulting in a total increase of additional costs of +55.4% for seismic improvements (step 1–5) added with +29.6% for valance boards, flooring and finishing (step 3b + step 6), amounting to +85.0% for a completed rubble stone school building, as compared to doing nothing at all (step 0).

Step 0. The foundation and walls of traditional buildings are constructed with rubble stone in mud mortar, without any inclusion of horizontal bands or vertical reinforcements. Doors and windows are made with a double frame, each placed on the outsides of the wall thickness, with planks on top serving as a lintel for the masonry above (**Figure 23B**). The walls have stone gables and the roof consists of wooden rafters, purlins and low-quality tin sheets. The floors are made of tamped earth, and no finishing works are applied such as plastering of walls and painting of woodwork.

Step 1a. The improved foundation includes stone soling and a layer of plain cement concrete (pcc) in the bottom of the trenches, as well as additional measures for the verandah and extra buttresses in the walls. Step 1b replaces all mud mortar with cement-sand mortar, which causes the biggest cost increase of these two steps.

Step 2a. Adding of extra buttresses in cement-sand mortar. Step 2b. Replacement of all mud mortar with cement-sand mortar for the rubble stone wall masonry walls. The replacement of mud in both foundation (step 1b) and walls (step 2b) together, roughly adds up to a third (+29.5%) of the total cost increase (including step 6).

Step 3a. Improving the roof structure by removal of the masonry gables and by adding full wooden trusses with cross-bracing, poles on the verandah, wooden gables and a stiff ceiling. These elements all contribute to the structural stability of the roof structure. However, step 3b which is applying of valance boards, has merely an esthetic function, but it represents a relatively high percentage of +4.0%, due to the high price of wood and the high labor-intensity.

Step 4. Addition of two continuous horizontal beams to the design, which is the bare minimum according to the Indian (IS 13828:1993, 2008) seismic code for non-engineered buildings. At step 4a the plinth beam and at step 4b the lintel, which acts as a top beam, are added. These beams are the thickest (6" and 4") and add around 9% to the cost increase. However, now that a lintel is installed above the openings, a huge cost saving of -7.5% can be made by installing single door and window frames, as opposed to the double set of frames at step 0. In dollars this means that the addition of 2 beams is just 235 U$ more expensive than doing nothing at all (by December 2018 rates).

Step 5. Addition of three more levels of 3" (75mm) thick horizontal reinforcements, being: Step 5a. Adding of top beam, thus placing the lintel at a lesser height within the wall, which also results in less height for all woodwork of doors and windows. Step 5b. Adding of sill beam below window level. Step 5c. Adding of stitches in all corners and t-sections of the walls. On average each step adds around 2% to the total increase of costs (200 U$ each) for a 3-classroom school, which is in line with the previous findings about the general costing of horizontal beams.

Step 6. Fully finished 3-classroom school as built by SSF, including: Step 6a. Flooring in the classrooms, on the veranda, and placing of aprons around the building. Although not part of the seismic strengthening of the building, this step is essential to make use of the school building, and therefore complements the total needed budget for a new construction project. This applies as well to Step 6b; Plastering of the walls and painting of the woodwork. These are also not part of the seismic requirements but will improve the quality, durability and lifetime of the building. Postponing of this step however may serve as a temporary cost-saving measure. It is remarkable to note that these non-structural actions combined are the costliest steps resembling nearly a third of the total cost increase. This is caused by the high price of stones in the floor and verandah, but also because finishing is very labor-intensive. For instance, the labor for plastering and painting (step 6b) represents half the total costs of this step (+49.8%).

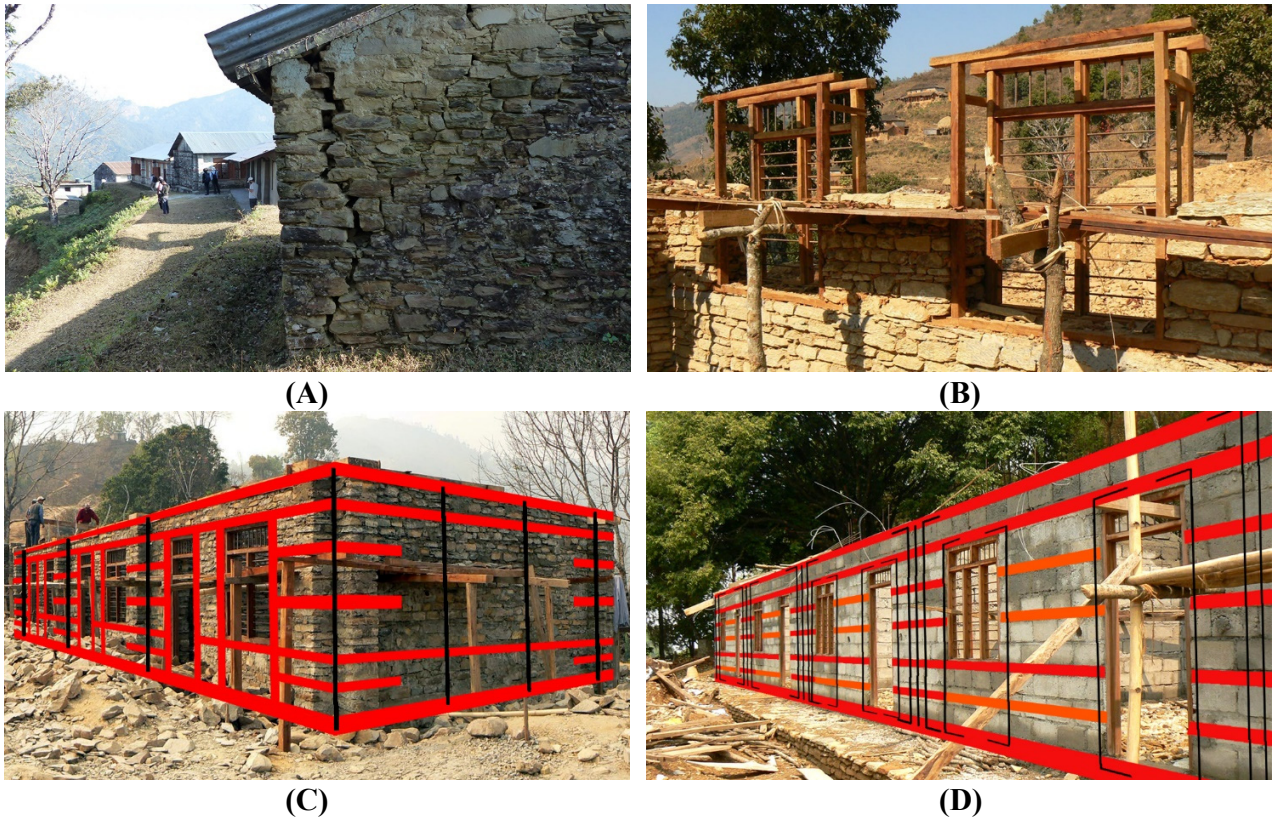


Figure 23. (A) *Traditional school building without horizontal reinforcements.* ***(B)*** *Double frames for doors and windows.* ***(C)*** *Rubble stone walls with extra horizontal stitches, additional vertical steel and boxed openings.* ***(D)*** *Concrete block walls with extra stitches and unreinforced concrete fillers (all by courtesy of Smart Shelter Research).*

Furthermore, two more steps were reviewed that are based on the current practice in Nepal after the 2015 earthquakes. The Nepal Reconstruction Authority (NRA, 2018) had published (and later removed) a number of school designs that are approved by the Nepali Government. It must be clearly noted that the authors are not in agreement with the addition of these extra reinforcements, and that this review is done solely for purpose of reviewing the increase of costs, which are added to **Table 14A** as follows:

Step 7. Addition of 2 extra layers of stitches in the walls, resulting in reinforcements at 7 horizontal levels (**Figure 23C**).

Step 8. Addition of vertical steel bars of 16 mm diameter that are inserted in all corners and t-sections, starting at the bottom of the foundation and bent into the top beam. A concrete core is cast around these bars against corrosion. The door and window openings are boxed by reinforced concrete posts, as also shown in **Figure 23C**.

As a final comparison, only the costing of the seismic improvements (step 1 to 5 minus the valance boards of step 3b) is considered. It shows that the biggest cost impact is made by the replacement of mortar in foundation and walls, representing more than half (+52.0%) of these additional costs, making this the most expensive intervention. The improved roof follows with +30.6%, addition of all 5 beams represents +13.3%, and the remaining +4.1% is for improving the foundation and adding of buttresses.

Table 14. *Cost differences between unreinforced and fully reinforced school buildings in (A) rubble stone masonry, and (B) hollow concrete block masonry, based on local village rates for 2017.*

		A. type I Rubble Stone			**B. type II Concrete Blocks**		
		in NRS	**%sub**	**%tot**	**in NRS**	**%sub**	**%tot**
Step 0	No reinforcements, stone in mud	1,168,723			788,211		
Step 1a	Improved foundation (+ buttresses)	47,802	4.1		20,299	2.6	
Step 1b	Cement mortar in foundation	138,795	11.9	16.0	103,428	13.1	15.7
Step 2a	Cement-sand mortar in stone walls	176,869		15.1			
Step 2b	Vertical steel bars in block walls				66,518		8.4
Step 3a	Improved roof structure	197,881		16.9			
Step 3b	Valance boards	46,344		4.0	122,989		15.6
Step 4a	Plinth beam on foundation	114,573	5.8		55,367	7.0	
Step 4b	Top beam on walls	38,426	3.3		23,694	3.0	
Step 4c	Reduction wooden frames	-88,028	-7.5	1.6			10.0
Step 5a	Lintel beam above openings	24,915	2.1		11,949	1.5	
Step 5b	Sill beam under windows	28,708	2.5		31,796	4.0	
Step 5c	Stitches in corners and sections	13,963	1.2	5.8	-4,947	-0.6	4.9
Step 6	Flooring and finishing	299,523		25.6	301,219		38.2
Finished 3-classrooms (as built by SSF)		2,162,150		**85.0**	1,520,523		**92.9**
Step 7	Reinforcements at 7 levels	2,191,741		2.5	1,559,792		5.0
Step 8	Vertical reinforcements in rubble	2,247,943		4.8			
	Total with additions			92.3			97.9

Note: The **bold** numbers represent the total increase in percentage.

4.5.4 From Unreinforced to Fully Reinforced Concrete Block Masonry

Similar to the review of stone masonry buildings, a set of drawings was prepared of an unreinforced building in hollow concrete blocks, which is then step-by-step improved, reinforced and fully finished. The cost differences, based on average village rates for group II, are added to **Table 14B** and amount to +54.7% for all seismic improvements plus +38.2% for flooring and finishing, totaling +92.9% between unreinforced and fully reinforced block masonry.

Step 0. The foundation is constructed with rubble stone in mud mortar, and the walls are built with 12 layers of low-quality hollow concrete blocks, in a cement-sand mortar mixture of 1:4, without any inclusion of horizontal bands or vertical reinforcements. Doors and windows are made with a single frame, on which blocks are directly placed without a lintel in-between. The walls have block masonry gables and the roof consists of a steel tube at the top, connected with steel tube rafters and purlins, and low-quality tin sheets placed over it. The floors are made of tamped earth, and no finishing works are applied such as plastering of walls and painting of.

Steps 1a and 1b are the same as with the stone masonry school, with a percentual increase that is comparable as well. Step 2 (improvement of walls) differs, as no buttresses are added to the block walls. Instead, the walls are reinforced with the inclusion of 3 vertical steel bars in all corners, 4 bars in the t-sections, and single bars next to all openings, that are all protected by filing the block cavities with a lean concrete mixture. This step 2c adds just over 8% to the overall cost increase.

Step 3a. The roof is improved by removing all masonry gables, adding steel poles on the verandah and by placing full steel tube trusses on the walls, which are inter-connected and closed-up at the sides with tin sheets. The structural stability is improved by installing cross-bracing elements at ceiling level. Together with improving the foundation (+15.7%), the strengthening of the roof is the most expensive seismic improvement (+15.6%).

Steps 4. Similar to the rubble stone walls, a plinth beam (step 4a) and a lintel beam at top level (step 4b) are added. As this is a stacking system of full-height blocks, the total height of the wall changes with each addition of horizontal reinforcing element. When adding the lintel, the number of blocks in height can be reduced from 12 to 11 rows. Both beams together increase the costs with 10%, whereas the addition of the 14″ (350 mm) wide plinth beam costs around 500U$ for 3 classrooms, vs. 200U$ for the 6″ (150 mm) wide lintel beam.

Step 5. Three more levels of horizontal reinforcements are added, being a top beam (step 5a) and a sill (step 5b). In both cases the number of blocks in the wall remains to be 11 rows high. The third level is the addition of stitches (step 5c), and to avoid hacking of blocks the horizontal space between the stitches is filled-up with a strip of unreinforced concrete as indicated in **Figure 23D**. Although step 5c includes all 5 levels of beams, this is actually cheaper than step 5b (4 levels), as at step 5c the walls plus beams need only 10 blocks in height. On average each of these 3 levels of reinforcement costs just 115U$ for 3 classrooms.

Step 6 is a fully reinforced and fully finished school building as built by SSF, split up in the non-structural additions of flooring (step 6a) and finishing (step 6b). These two non-structural phases combined (+38.2%) are almost equally expensive as seismically improving the foundation, walls, and roof (steps 1 to 3 amount to +39.7%). Again, this shows that the cost of including seismic strengthening measures is relatively low, in relation to the total cost of construction.

Step 7 adds two more levels of stitches as is currently practiced in Nepal. However, to incorporate all these extra layers means extra strips of unreinforced concrete (**Figure 23D**) and adds an extra wall height of 6" (150mm) since it is not possible to remove one row of blocks due to insufficient ceiling height. Step 8, vertical steel reinforcements, was already carried out at step 2c.

Lastly, for the concrete block schools the overall increase of +92.9% is divided into +54.7% for seismic improvements, and +38.2% for flooring and finishing. When only considering the costs for seismic interventions, the division is fairly equal for improvement of the foundation (+28.7%), improvement of roof (28.5%) and adding of all horizontal beams (+27.4%). The remainder (+15.4%) is used for strengthening of the walls.

4.5.5 Bills of Quantity

The previous chapters have compared the costing of different techniques, their separate elements and possible technical alternatives. To make all the comparisons useful and available to others, the Bills of Quantity (BoQ) for construction of one-story school buildings in the different contexts of Nepal are summed up in **Table 15**. These BoQ's list the needed quantities of materials, wages and transportation for 4 types of construction, being i) rubble stone walls with wooden roof, ii) rubble stone walls with steel roof, iii) concrete block walls with wooden roof, and iv) concrete block walls with steel roof. As a rule of thumb, building volumes should not exceed the maximum ratio of 1(length):3(width), which in practical terms means that a volume should not exceed three classrooms in a row. Therefore, the table includes the total quantities for buildings of each technique with 2 and with 3 classrooms, so that designs with four (2+2) or five (2+3) rooms can be estimated as well.

Table 15. *Bills of Quantity of materials, labor wages and transport fees, for designs with 2 and 3 classrooms, for all four types of building techniques.*

		i) rubble-wood		ii) rubble-steel		iii) block-wood		iv) block-steel	
	Unit	2 room	3 room	2 room	3 room	2 room	3 room	2 room	3 room
soling stones	cft	492	716	492	716	444	650	444	650
mountain stones	cft	2,059	2,839	2,059	2,839	973	1,345	973	1,345
coarse river sand	cft	1,126	1,575	1,126	1,575	645	923	645	923
aggregates 3/4" for concreting	cft	446	632	446	632	320	464	320	464
aggregates 1/2" for grouting	cft	0	0	0	0	33	50	33	50
fine plastering sand	cft	267	371	267	371	323	327	323	327
mud mortar aprons & verandah	cft	63	76	63	76	67	80	67	80
cement (opc) mortar & concrete	bag	249	349	249	349	175	251	175	251
concrete blocks 15 x 8 x 6 inch	block	0	0	0	0	648	917	648	917
concrete L-blocks	block	0	0	0	0	60	80	60	80
steel rods 10mm	Lft	824	1,105	824	1,105	672	1,053	672	1,053
steel rods 12mm	Lft	1,153	1,602	1,153	1,602	1,681	2,504	1,681	2,504
steel rods 7 mm for stirrups	Lft	2,370	3,321	2,370	3,321	1,303	1,862	1,303	1,862
binding wire per kg	kg	6.5	9	6.5	9	7	10	7	10
tin sheets 26 gauge (6 p. bundle)	bundle	6.5	9.5	10	12.5	6.5	9	9.5	12
steel truss pipe 2" diameter	Lft	0	0	372	523	0	0	348	490
steel truss pipe 1.5" diameter	Lft	0	0	629	895	0	0	590	842
Sal wood roof works & frames	cft	139	196	32	48	131	185	32	48
local wood for formwork	sq.ft	126	176	126	176	113	160	113	160
triplex board for ceiling	sq.ft	495	743	0	0	495	743	0	0
unskilled labor per day	wage	80	113	82	116	65	90	65	93
skilled labor per day	wage	239	336	224	318	210	295	194	280
tractor load per 2500 kg	trip	5.5	7.5	5.8	7.8	8.0	11.5	8.0	11.5
percentage of costs covered	%	94%	95%	97%	97%	93%	94%	93%	93%

All elements are converted into separate materials and costs in such way, that it is just a matter of filling in the going prices and rates for each item. This way the villagers can compare which technique is cheapest to build in their village. Items can also be easily changed according to the needs and requirements of the project. For instance, the 7mm ribbed steel stirrups or the round steel truss pipes are expressed per total length, so that this can be simply changed to 6mm plain steel or aluminum truss profiles, if locally preferred. The amounts in **Table 15** make up for between 93% and 97% of all total costs for materials, labor and transportation, with the remaining percentages mainly for finishing such as paints and for local transportation on site. By adding 10% for contingencies, the estimations give a very accurate representation of the actual construction costs for these particular designs, at any given time. For other building dimensions a set of adjusted drawings and estimates must be prepared, but with the use of the existing Master sets this can be done rapidly. In case of adding or removing certain earthquake-resistant measurements, these costs can be easily added or subtracted by using the percentages as presented in the previous sections.

4.6 Conclusion

Detailed estimations of three different construction types of school buildings have been analyzed and compared based on local village rated costing data of 19 villages, as well as on generally applicable District Rates (DR) of Kaski District in Nepal, for the period between 2007 and 2017. Master Estimates were divided into the five main building phases of foundation, walls, roof, floor and finishing, and then further broken down into costs for materials, labor and transportation, based on local material constants, labor outputs and transportation fees. These cost comparisons give a detailed insight into the distribution of the costs, the pricing of individual materials and construction elements, the effect of price fluctuation on the total costs, and the cost implications of different solutions for seismic measures; for different time frames and for the different geographical contexts of Kaski District. The following is concluded:

- The distribution of costs, which is based on relative figures, only gives insights into the comparison of data within a specific area and during a limited period of time. For instance, in 2007 the wall portion had the highest influence on the costs, whereas in 2017 the roof construction plays a more prominent role. No general or useful pattern was detected that allows us to predict the situation 5 or 10 years ahead, as prices will continue to fluctuate due to changing markets or unforeseen impacts, such as the 2015 Gorkha Earthquake. It means that current trends and their cost implications must be constantly analyzed and updated.

- No similarities were found between the different costing approaches of the local village rates versus the general District Rates. Overall, the DR were much higher compared to the local rates in 2007, and although this difference became less in 2017, this is no guarantee for any future scenario. Material rates deviate largely between the two costing systems, especially the prices for local materials such as mountain stones and Sal wood.

- A cost check after the 2015 Gorkha Earthquake in Nepal concludes that predicted exorbitant price hikes, such as doubling or tripling of prices, were not noticeable in Kaski and Gorkha Districts.

- Location has a massive impact on the sourcing and costing of materials. For instance, the distance between Makaikhola and Gahate is only 4 kilometers, but since Gahate owns a community forest and Makaikhola does not, it results in a big cost difference for the roofing phase between the villages. The DR do not reflect such variations at the micro level, but they represent national trends and fluctuations of the global market prices. They are not representative for the actual situation in the hills and mountain areas, as they insufficiently address local factors such as availability of materials, accessibility to the site, or preferences of the villagers.

- In 2017, the figures indicate that a school building in cement blocks with a steel roof has become the cheapest construction type for all three different contexts (group I-III). However, this may not be the case further up into the mountains, or in other districts, where transportation and distance to resources may be the critical factor. To rapidly determine which type is cheapest to build with in any village or setting, the Bill of Quantities for 8 different school types is summarized in **Table 15**, by listing the needed quantities of materials, wages and transportation. These estimations give a very accurate and complete representation (93-97%) of the actual construction costs for these particular designs, at any given time. Ultimately, the choice of construction is up to the villagers, who besides costing may put a lot of consideration on other factors such as location, accessibility, availability, custom and preference as well.

- The last section analyzes the price implications of adding or removing certain seismic features, such as better-quality mortars, horizontal bands and/or vertical reinforcements. Based on the 2017 local village rates, the total cost increase from an unreinforced building into a fully reinforced school is 55.4% for seismic improvements, with an addition of 29.6% for flooring and finishing, which amounts to 85.0% for rubble stone masonry, and to 54.7 + 38.2% = 92.9% for cement block masonry. In terms of seismic reinforcements, upgrading of the mortar quality in foundation and walls, and upgrading of the roofing system have the biggest impact on the cost increase. Adding of horizontal bands however (step 5) represents just about 1.5% (for rubble stone) to 3% (for concrete blocks) of cost increase per band on average. This is a very positive outcome as it means that the inclusion of these important seismic features is not that expensive, and that there is basically no financial obstacle to incorporate horizontal beams and stitches in new constructions of schools and houses. To put this further in perspective, the cost of plastering and painting (step 6b), which does not contribute to the seismic performance of the building, is more expensive than all possible horizontal and vertical reinforcements combined.

In theory, significant cost savings can be made by replacing rubble stone foundations with plum concrete foundations, cement mortar with mud mortar (highest cost impact) and reducing of reinforcing elements. However, it must be explicitly noted that this chapter only examined any possible cost implications, and that this chapter gives no indication nor opinion about which construction type performs better during a seismic event. The validation of such implications involves structured and in-depth scientific research, which is a main goal of the SMARTnet project, as described in this thesis.

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Chapter 5

Rubble Stone Masonry buildings with Cement Mortar: Base Shear Seismic Demand Comparison for Selected Countries Worldwide

Summary

Full base shear seismic demand analyses with calculated examples for heavy stone masonry buildings are not present in the literature. To address this shortcoming, this chapter performs analyses and calculations on two nominally reinforced rubble stone masonry house and school designs, as typically built in Nepal. The seismic codes are literally applied for countries where the technique is still allowed, being Nepal, India, China, Tajikistan, Iran and Croatia; or should be reintroduced based on current practices, such as in Pakistan, Afghanistan and Turkey.

First, this chapter compares the base shear formulas and the inertia forces distributions of these codes, as well as material densities, seismic weights, seismic zoning, natural periods of vibration, response spectra, importance factors and seismic load combinations. Large differences between approaches and coefficients are observed. Then, by following Equivalent Lateral Force-principles for Ultimate Limit State verifications ($10\%PE_{50y}$), the base shear and story shears are calculated for a design PGA of 0.20g, as well as the effects of critical load combinations on the Axial Forces (*N*), Shear Forces (*V*) and Bending Moments (*M*), acting on the lateral-resisting elements.

It is concluded that Pakistan has the most tolerant code, Nepal represents an average value, whereas India and China are most conservative toward the case study buildings. Overall, it is observed that heavy-masonry-light-floor systems with negligible diaphragm action behave different under seismic motion than most other building typologies. Given the observations in this chapter, the applicability of conventional ELF, S-ELF and S-Modal methods for heavy masonry buildings is questionable. The codes however do not introduce modified approaches that address these differences. Possible implications of the exclusion of plinth masonry and large portions of seismic weight need further assessment and validation, for which different (possibly more sophisticated) concepts must be considered, such as the equivalent frame method or distributed mass system.

Note: As each country uses different symbols for similar formulas and expressions, it is decided not to compile a list of symbols, but to denote all symbols as footnotes under the respective tables.

5.1 Introduction

In-depth technical verifications or validated calculations for stone masonry buildings are not available in the literature nor national codes. The empirical knowledge is based on a few publications from the 1980s which have not been updated since, as concluded in the previous chapters of this thesis. It was already noted in 1977 that "a review of the earthquake codes of various countries shows that much of the information is empirically based and not theoretically derived. In that respect, the recommendations must be subject to continuous review and change as more data become available" (Arya, 1977). Furthermore, Bertero and Bertero (2002) state that "codes and standards should be simple enough so that they can be applied effectively according to the education (knowledge) of the professionals involved (designers, builders, governmental bodies) as well as the owners, but without compromising

the reliability of the structure. (…) Codes should reflect the most reliable procedures that can be developed according to the state-of-the-art in seismic engineering." Effectively, for "non-engineered" structures this has not been undertaken to date.

This chapter analyzes and compares the seismic demand in terms of total base shear and the load combinations for Ultimate Limit State (ULS) verifications, as dictated in the seismic codes. This is done for those countries where this technique is still allowed, plus selected countries where it potentially could (or should) be reintroduced based on current practices and needs. The analyses are carried out with specific focus on "nominally reinforced masonry (NRM) that consists of random rubble stone with cement mortar and wooden diaphragms", as detailed in Chapter 2. Random rubble refers to stones that are uncut, unsquared, irregularly shaped and un-dimensioned, whereas NRM refers to loadbearing masonry walls with the inclusion of nominal reinforcements; in this case continuous horizontal bands. Following the philosophies of Arya and Bertero & Bertero, and in the spirit of "non-engineered seismic design", a simplified approach performed by hand calculations is preferred wherever possible, as opposed to computer-aided modeling.

Many comparisons between seismic codes are found in the literature between a countries' national code and leading codes from the US, Europe, Japan and New Zealand, such as for India (Dhanvijay et al, 2015), Pakistan (Ali et al, 2017), Azerbaijan (Zeynalov et al, 2013) or Iran (Imashi and Massumi, 2011). A more regional approach compares the situation between neighboring countries, for example Nepal with India (Neupane and Shreshta, 2015) and China (Tamrakar and Chen, 2017), or Russia with Armenia and Uzbekistan (Mukhadze and Timchenko, 2000). Overall, the following generalities are observed. Firstly, most studies focus on particular segments, formulas or design parameters within the codes (for instance Xiaoguang et al, 2012 who compare eight Asian countries), but they do not cover the complete design process of a particular building type or technique. Secondly, when a calculation example is included, these are almost exclusively for medium-to-high-rise buildings with concrete or steel frames (Khose et al, 2012), Shi et al, 2016). However, seismic code comparisons for loadbearing masonry structures such as Vratsanou (2000) and Haziq and Morisako (2017) are less common, whereas comparisons including seismic calculations for stone masonry were not found.

All these shortcomings are addressed in this chapter, by presenting case study designs of a two-story house and a one-story school building in rubble stone masonry as commonly built in the Himalayan Region, for which the necessary comparisons and calculations are made to determine their full seismic demand. The objective of this chapter is two-fold:

(i) to discuss the complete design process of rubble stone masonry buildings according to literal application of selected seismic codes, in order to identify upper and lower bounds for the seismic demand on the wall panels;

(ii) to provide a systematic comparison of the most recent base shear formulas, their individual parameters and distribution criteria of inertia forces, as well as material densities, seismic weights, seismic zoning, soil conditions, natural periods of vibration, response spectra, building importance and seismic load combinations, in order to identify issues that need validation.

These investigations are carried out specifically for rubble stone masonry buildings, but also face issues of general significance. The determined seismic demands must be checked against the corresponding structural capacities in relation to the mechanical properties, to be published in follow-up papers.

5.2 Rubble Stone Masonry: Case Study Buildings and Selected Codes

Chapter 3 concludes that no consensus was found on any of the design specifications and main dimensions for rubble stone masonry buildings, and globally the differences vary greatly. Since the projects of SSF in Nepal have withstood the 2015 Gorkha earthquakes without any significant damage, the Nepalese context is taken as the reference for the development of two case study buildings in rubble stone masonry with cement mortar. One is a typical rural house design as published in the reconstruction catalogue after the earthquakes (DUDBC, 2015), and the other a mountain school as built by SSF. These are designed in such way that they have comparable weights (total Dead Load), as a fair starting point for all upcoming (and future) comparisons. The two-story house with verandah has 450mm thick walls (**Figure 24A**); the three-classroom school is one-story high with 350mm thick wall and cross-spacing of 6m (**Figure 24B**). Both are raised on a continuous masonry plinth that is topped with a reinforced concrete tie-beam and filled with tamped soil (total height of plinth is 450mm), have light wooden floors and roofs, and the walls are reinforced with horizontal concrete bands and stitches. Openings are not lined (boxed) with reinforcements such as vertical concrete posts or steel bars, and neither vertical reinforcements nor buttresses are included at critical plan intersections, based on the hypothesis that these are not needed. The good performance of the SSF schools (although these did include buttresses) during the 2015 earthquakes is a first indication for this hypothesis. The case study buildings will be used for validation of such assumptions, as well as for full comparison and discussion of the seismic design specifications, for selected countries worldwide.

The codes of the following countries are analyzed in further detail, and applied as literally as possible, aiming to avoid opinion and interpretation. It is important to note that these are read and analyzed in their original languages by native speaking experts; all mentioned in the acknowledgments. Currently, rubble stone masonry buildings in seismic areas are only allowed in seven countries in the world, being Nepal, India, China, Tajikistan, Georgia, Iran and Croatia. For Nepal the recently revised seismic code of 2020 is included, and for China their rural seismic code is analyzed. Georgia is currently in the process of adopting Eurocode and development of a National Annex to Eurocode 8, therefore their current seismic code PN 01.01-09 (2012) is excluded. Although prohibited by their codes, three more countries where stone masonry is still abundantly practiced are added, being Pakistan (based on the Uniform Building Code of 1997), Afghanistan (based on ASCE-7-2010) and Turkey (largely based on ASCE-7-2016). All codes are simply referred to by their country names, or abbreviated as follows:

Nepal, NEP-20, NBC-105:2020 (2020)
India, IND-16, IS-1893(pt.1):2016 (2016)
Pakistan, PAK-07, BCP-SP-07 (2007) and UBC-97, UBC-1997 (1997)
Afghanistan, AFG-12, ABC-2012 (2012)
US-based, ASC, ASC-10, ASCE/SEI-7 (2010) and ASC-16, ASCE/SEI 7-16 (2017)
China, CN-JGJ (rural), JGJ 161-2008 (2008) and CN-GB (national), GB 50011-2010 (2016)
Tajikistan, TAJ-18, SNiP RT 22-07-2018 (2019)
Iran, IRN-15, Standard 2800 (2015)
Turkey, TUR-18, TBDY (2018)
Europe, Eurocode 8, EC8, EN 1998-1:2004+A1 (2013)
Croatia, CRO-11 (National Annex to EC8), nHRN EN 1998-1:2011/NA (2011)

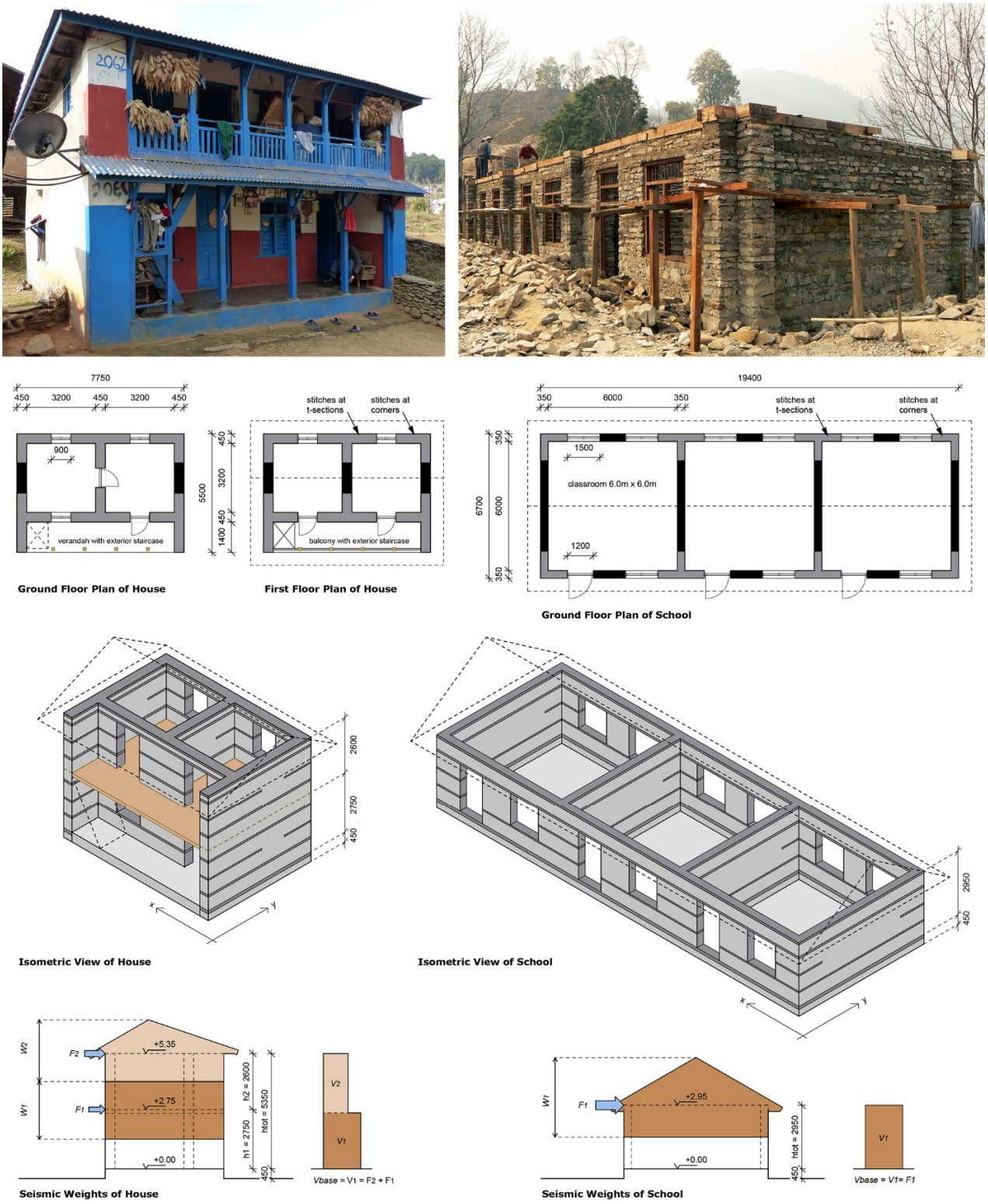


Figure 24. *Case study designs based on typical constructions in Nepal: (A) Two-story house with verandah. (B) One-story school with three classrooms (all by courtesy of Smart Shelter Foundation).*

5.3 Determination of Static Loads and Seismic Weights

5.3.1 Seismic Behavior of the Case Study Buildings

All selected codes include clauses or checklists to determine whether a structure is classified as "regular or irregular", for which symmetry and uniformity are important concepts. Buildings with a simple geometry, a regular structural arrangement and uniformly distributed mass and stiffness in both horizontal plan and vertical elevation, generally suffer less damage than buildings with irregular configurations. Vertical irregularity is no issue for the one-story school, and in the two-story house all walls are aligned directly on top of each other (= no discontinuity), to ensure clear and direct load paths to the foundation. Openings are kept small, horizontally aligned in height, and placed right above each other in both stories, with one deliberate exception in the interior wall to analyze the effects of this deviation. Further, both stories have an almost identical distribution of mass, with similar strength and lateral stiffness of the lateral-resisting elements (= no soft or weak story).

In the horizontal direction, plan regularity is achieved by an evenly distributed alignment of shear walls in both orthogonal axes, without re-entrant corners in plan or excessive perforations in the floors. Although the house plan is not entirely symmetric in the Y-direction due to the veranda, a simplified check by following the method in ASC-16 confirmed that it is within acceptable limits to avoid torsional irregularity, as "the center of weight in each story shall be located not further from the geometric centroid of the diaphragm than 10% of the length of the diaphragm parallel to the eccentricity". The elongated floor plan of the school falls within prescribed limits as well, where the length-to-width ratio should not exceed 3:1 as mentioned in the design codes for low-strength masonry of India (IS:13828-1993, 2018) and Nepal (NBC202:2015, 2015). In EC8 this is maximized to 4:1, whereas IRN-15 reduces this to 2:1. EC8 further cautions against irregular plan shapes such as L-, T- and U-configurations, which need to be divided into rectangular units by means of seismic separation gaps. Some codes give maximum lengths of such volumes, ranging from 25m (IRN-15) to 60m in Intensity zone 8 and 45m in zone 9 (TAJ-18). Overall, the house and the school can be classified as regular buildings. In terms of analysis, simple regular structures are generally subject to less uncertainties in the prediction of their seismic behavior, which is reflected in the choice of the method of analysis, explained further on.

In-plan torsional effects are also related to the diaphragm action of the floors and roofs, which are generally divided into flexible or rigid (or semi-rigid in PAK-07, AFG-12). By introducing stiff ceilings in the floors of the house design, and diagonal cross-bracing in the roof constructions of both house and school, these may act as semi-rigid diaphragms at best. However, since such strengthening measures are not common practice in non-engineered construction, the light wooden diaphragms are assumed to be flexible. The flexible range defines "the diaphragm stiffnesses for which the walls behave as though they are isolated elements, and an incremental diaphragm flexibility has no effect on the wall behavior" (Nakamura, 2017). Flexible diaphragms do not benefit from the advantages of rigid diaphragms (for instance concrete slabs), such as redistribution of horizontal seismic forces between the different lateral-resisting elements (proportional to their lateral stiffness), and increased box behavior of the structure by improving the out-of-plane stability of the walls. Light diaphragms do not increase the bending moment and shear force capacities of the walls since the added axial stresses are negligible, but they do have the advantage of not generating significant additional inertia forces, nor torsional effects.

Given all the above, the case study buildings, which are characterized by heavy stiff walls and light flexible diaphragms, behave differently from most common structures (such as frame buildings with heavy slabs). As a main difference, most of the seismic forces are generated by the mass of the heavy stone walls, whilst the contribution of the light diaphragms is nearly negligible (97.5% versus 2.5% of mass, as shown in the next section). An important difference with rigid diaphragms is that, for flexible diaphragms, the floor inertia forces are distributed to the vertical lateral-resisting shear walls in proportion to tributary areas. Further, the overall stability, prevention of out-of-plane failure and delamination of the wall wythes are enhanced by the deliberate addition of continuous reinforced concrete tie-beams at various levels, as well as by the limited plan dimensions, use of cement mortar, and inclusion of through-stones in the masonry patterns. Due to these intentional considerations, the immediate attention of this research is on ultimate strength verifications (internal forces, in-plane stiffness), which are expected to be more demanding than the serviceability ones (stress checks, displacements; to be addressed in separate future research when more detailed and reliable computer-aided models are to be developed) for these stone masonry buildings. It is noted that in some countries, the type of diaphragm has a direct consequence for the code-required method of analysis, as explained further on.

5.3.2 Total Dead Load of the Case Study Buildings

The most important factor that determines earthquake inertia forces in a building is its mass (Newton's Second Law of Motion). Unfortunately, in rural and mountain areas the construction materials are generally heavy, such as bricks, stones and to a lesser extent earth. For both buildings the self-weight, or total Dead Load (*DL*) of structural and non-structural elements, is determined according to the national codes for "Design Loads", which mention nominal or characteristic densities of materials. The Nepalese code NBC 102:1994 (2007) refers to Indian code IS:875(pt.1)-1987 (2018) and therefore the total DL is the same for both countries. Pakistan and Afghanistan also use identical densities, but from different versions of ASC (ASCE 7-93 (1994), ASC-10). China includes densities in GB 50009-2012 (2012), Iran in NBRI-6 (2013), Turkey in TS-ISO-9194 (1997), and all European countries refer to EN 1991-1-1:2002/AC:2009 (2009). For TAJ-18, a selection of densities is mentioned in an annex of the Russian code for "Thermal Performance of Buildings" (SP 15.13330.2012, 2012), but basically self-weights must either be requested from material suppliers or taken from different Russian material norms, such as for stone masonry (GOST 4001-13, 2019), concrete (SP 63.13330.2018, 2019) and timber (SNiP II-25-80, 1989).

For calculation of *DL* of the buildings, the densities for stone masonry, concretes, mortars and woods are expressed in kN/m^3, and the self-weights of plywood and roofing sheets in kN/m^2. Tajikistan further adds a safety factor γ_f to all materials for the determination of *DL* (and *LL* as well, next section). When codes give ranges of densities, an average value is taken, such as for reinforced concrete in India, or timber in China. Two scenarios are determined, being a "lower-density" version where materials of lighter weights such as sandstone and softwood are used, and a "higher-density" version based on granite stone masonry for the walls and hardwood for the roof, floors, doors and windows. The Indian, Iranian, Turkish and US-based codes define clear values for different types of rubble stone masonry based on stone type, whereas China makes a distinction between degrees of coarseness of the stone finishing. In Russia and Europe the values for stones and mortars are mentioned separately, and combined into stone masonry with a weight ratio of 70%-30%. Further, a layer of interior cement-sand wall plaster is included as this adds significantly to the total weight of the house and school, namely +5% and +7% respectively.

Table 16. *Lower-density scenario of materials and distribution of Dead Loads for the house and school.*

Country and Code for Material Densities		**Nepal** and NBC 202-1994 **India** IS.875(p.1)-2007		**Pakistan** and ASCE-7 (1993) **Afghanistan** ASCE-7 (2010)		**China** GB 50009-2012		**Tajikistan** SP 15.13330.2012	
Materials	unit		density		density	ψ_G	density	n_c	density·γ_f
sandstone masonry	kN/m^3		22.00		21.52	1.0-0.95	20.80	0.9	22.46·1.1
reinforced concrete	kN/m^3		23.48		23.56	1.0-0.95	24.00	0.9	24.52·1.1
mortar / plaster	kN/m^3		20.40		20.42	1.0-0.95	20.00	0.9	17.65·1.3
construction wood	kN/m^3		5.05		4.41	1.0-0.95	5.00	0.9	4.90·1.1
plywood	kN/m^2		0.065		0.053	1.0-0.95	0.090	0.9	0.093·1.3
roofing sheets	kN/m^2		0.045		0.045	1.0-0.95	0.050	0.9	0.045·1.3
Self-weights, *DL*	unit		%		%		%		%
house, *DL* plinth	kN	114.4	7.1	112.9	7.2	111.2	7.3	117.7	7.2
house, *DL* walls	kN	1447.5	91.1	1421.3	91.2	1384.0	90.8	1470.2	91.0
house, *DL* roof	kN	16.8	1.1	15.0	1.0	17.6	1.2	17.0	1.1
house, *DL* 1st floor	kN	10.5	0.7	9.1	0.6	10.9	0.7	10.8	0.7
house, total *DL*	kN	**1589.2**		**1558.3**		**1523.7**		**1615.7**	
school, *DL* plinth	kN	222.5	13.9	219.6	14.0	216.3	14.0	228.9	14.1
school, *DL* walls	kN	1338.5	83.6	1315.0	83.7	1281.4	83.1	1352.2	83.3
school, *DL* roof	kN	40.6	2.5	36.2	2.3	44.1	2.9	42.9	2.6
school, total *DL*	kN	**1601.6**	(+0.78)[1]	**1570.8**	(+0.80)[1]	**1541.8**	(+1.19)[1]	**1624.0**	(+0.51)[1]
Country and Code for Material Densities		**Iran** NBRI-6 (2013)		**Turkey** TS-ISO-9194 (1997)		**Croatia** EN 1991-1-1:2002		**Turkey** "Higher density"	
Materials	unit		density		density		density		density
sandstone masonry	kN/m^3		22.60		26.50		22.50		27.50
reinforced concrete	kN/m^3		24.50		23.05		25.00		25.50
mortar / plaster	kN/m^3		20.60		20.60		19.00		20.60
construction wood	kN/m^3		4.02		4.02		4.40		6.86
plywood	kN/m^2		0.065		0.075		0.075		0.150
roofing sheets	kN/m^2		0.045		0.150		0.045		0.150
Self-weights, *DL*	unit		%		%		%		%
house, *DL* plinth	kN	118.1	7.3	128.9	7.0	118.7	7.2	136.4	7.0
house, *DL* walls	kN	1487.4	91.3	1690.7	91.3	1480.2	91.2	1765.2	90.6
house, *DL* roof	kN	14.3	0.9	21.9	1.2	15.5	1.0	30.4	1.6
house, *DL* 1st floor	kN	8.6	0.5	8.8	0.5	9.5	0.6	15.5	0.8
house, total *DL*	kN	**1628.5**		**1850.3**		**1623.8**		**1947.5**	(+27.8)[2]
school, *DL* plinth	kN	229.8	14.0	250.7	13.5	230.8	14.1	265.4	13.5
school, *DL* walls	kN	1374.0	83.8	1553.7	83.4	1364.0	83.5	1621.8	82.5
school, *DL* roof	kN	35.6	2.2	57.9	3.1	38.5	2.4	79.8	4.1
school, total *DL*	kN	**1639.4**	(+0.67)[1]	**1862.3**	(+0.65)[1]	**1633.3**	(+0.58)[1]	**1966.9**	(+27.6)[3]

Note: The **bold** numbers mark the total Dead Load of the case study buildings

ψ_G = Combination coefficient for determination of seismic weights (Table 17); 1.0 for 1 story and 0.95 for 2 stories

n_c = Combination coefficient for determination of seismic weights (for use in Table 17)

γ_f = Safety factor

[1] Percentual difference between self-weight of house and school designs

[2,3] Percentual difference between house and school with lowest (China) and highest (Turkey) self-weights

The densities of different types of timber are either taken from national codes, publications on forestry and online databases such as Orwa, (2009). For the lighter scenario, commonly used softwoods are Blue Pine (*Pinus Wallichiana*) in Nepal and India (local names Salai and Kail), and Poplar (*Populus L.*) in Pakistan (local name Safeda) and Afghanistan (Bhatt, 2016). Poplar in Turkey (*Populus Alba,* local name Dev Kavak) has a slightly lower density, and also in Iran this type is cultivated for construction purposes nowadays (Arian et al, 2007). China has included a special category of "ordinary wood" for rafters and purlins, covering all kinds of pines, cedars, willows and poplars. The forest area in Tajikistan is estimated at just 3% of the total land area. Therefore, lugging of timber is prohibited since the 1950s and construction woods such as Poplar and Spruce (*Picea spp.*) are imported from Kazakhstan and Russia (Kirchhoff and Fabian, 2010). Georgia on the other hand is covered by 40% of forestation, including vast quantities of Spruce (World Bank, 2020). For Croatia, an average density was taken between softwood strength classes C24 and C30 for Poplar and Spruce (EN 1912:2012, 2012). For types of hardwood in the calculations of the "heavy scenario" the following values are used. Both Nepal and India often use Sal (*Shorea Robusta*), although this species is depleting rapidly. In the other countries different types of oaks are more common, such as Kharsu Oak (*Quercus Semecarpifolia*) in Pakistan and Afghanistan, Chinese Oak (*Quercus Variabilis*) in Tibet, Chestnut Oak (*Quercus Castanefolia*) from the Zagreb Mountains in Iran, Turkish Oak (*Quercus Cerris*), Georgian Oak (*Quercus Ibericus*), and for Europe the strength class D40 for Oak and Ash is taken. For plywood, India, Russia and ASC mention only one density which can be used to calculate different thicknesses of sheets, whereas China, Turkey and Europe give different densities for different qualities. Lastly, the weight of the roofing sheets (plus 20% extra length for overlaps) is cross-checked with actual data from Nepal for 26-gauge (= measure of thickness) corrugated sheets, which weigh 66kg per bundle of 72 feet length (6x12ft., 9x8ft. or 12x6ft. sheets). Only the Turkish code mentions a significantly higher weight for roofing sheets compared to all other countries.

All relevant densities are collected in **Table 16**, which further includes the total calculated *DL* for both case study buildings, based on the lower-density scenario. It shows that the self-weights for the house and school are nearly identical, with a difference of less than 1% for each country. The Turkish values for sandstone and granite are the highest, resulting in the highest *DL* overall. In the upcoming calculations the sandstone scenario is taken as the lower limit, and the Turkish granite scenario (last column in the table) as the upper limit. Since the generation of seismic force is directly proportional to weight, such significant differences must be considered; both designs in Turkey (higher-density) are nearly 28% heavier than in China (lower-density). The influence of the other materials, such as the difference between softwood and hardwood, is almost negligible. Further, the total *DL* is split into portions of walls and diaphragms, which confirms that almost all mass is located in the walls, with an overall average of 97.8% versus 2.2% in the floors and roofs in the house, or 97.5%-2.5% in the school, or roughly 97%-3% in both cases when excluding the plinth; for the sandstone scenario.

5.3.3 Seismic Weights of the Case Study Buildings

The total Seismic Weight (W_{tot}) included in base shear calculations, is usually defined as the sum of Dead Load (*DL*) plus portions of Live Loads (*LL*) and Snow Load (*SL*), for which combination coefficients are given in the seismic or loading codes. All seismic codes indicate that wind loads are not considered simultaneously with earthquake loads. In both buildings, the ground floor is built "on grade" meaning there is no connection between plinth and floor, thus *LL* at this level is excluded as the loads are directly transferred to the ground. All codes also exclude *LL* on (pitched) roofs for determination of W_{tot}, resulting in no *LL* whatsoever for the schools.

Values for *LL*, called Imposed Loads in India (IS:875(pt.2)-1987, 2018), Occupancy Loads in Nepal (NBC 103:1994, 2007) or Long-term Loads in Tajikistan (SNiP RT 20-01-2012, 2016), are shown in **Table 17**, ranging between 1.5-2.0 kN/m^2 on residential floors, and 2.0-4.0 kN/m^2 on corridors and verandas. The Turkish values are taken from the loading code TS-498 (1997). All countries include only a portion of *LL* in their seismic weight calculations, for which the combination coefficients are defined as ψ_c in China, n_c (TAJ-18, TUR-18), ψ_2 in Europe (EN 1990:2002+A1, 2010), or C_{comb} (remaining codes). The values range between 0.2 in Iran to 0.8 in Tajikistan. Turkey and Europe divide their coefficients based on occupation, being 0.3 for residential and 0.6 for school functions.

For inclusion of snow in seismic design, the determination of *SL* is either given in the seismic codes (PAK-07, AFG-12), the loading codes (China, Tajikistan, Iran), or in separate snow codes in India (IS:875 (Part 4)-1987, 2018), Nepal (NBC 106:1994, 2007), Turkey (TS-7046, 1989) and Europe (EN 1991-1-3:2003, 2009). Some seismic codes only include *SL* for areas with severe snowfall that exceed design densities of 1.4 kN/m^2 (AFG-12) or 1.5 kN/m^2 (IND-16, PAK-07 and IRN-15). In Europe *SL* is only considered in the Nordic countries and for altitudes above 1,000m, whereas in NEP-20 snow is not mentioned at all. In the remaining countries, a portion of *SL* is always included in W_{tot}, ranging from 20% in Turkey to 50% in China and Tajikistan (here *SL* is called a Short-term Live Load). The density of snow depends on water content, meteorological conditions, freshness, settling and compaction (Meløysund et al, 2007), where 1.5 kN/m^2 translates to a layer of 1.5m of fresh snow or 75cm of settled snow (EC1-1-3). However, such scenarios are generally limited to very high altitudes, as confirmed in the geographical snow tables in all codes, where ground values seldom exceed 1.5 kN/m^2. For instance, in both Tibet and Xinjiang Provinces in China, most design densities stay well below 1.0 kN/m^2 for a recurrence period of 50 years. Furthermore, areas with severe snowfall are usually sparsely inhabited, whereas flat roofs are more common than pitched roofs due to high wind velocities, and people generally take care in removing heavy packs of snow as quickly as possible. The Indian code for load combinations (IS:875 (Part 5)-1987, 2018) further states that "the simultaneous occurrence of maximum values of wind, earthquake, imposed and snow loads is not likely." For all the above reasons, the portion of *SL* is excluded from further calculations, as this is assumed to occur in exceptional cases only. It is however acknowledged that *SL* can add significantly to W_{tot}, such as an additional 244kN (roughly 6 times DL_{roof}) for the school and 94kN (nearly 5.5 times DL_{roof}) for the house, as calculated with the Indian code for a design snow load of s = 1.5 kN/m^2.

Table 17 further shows the calculated seismic weights for the house and school. All codes include full *DL* except TAJ-18, which introduces a combination coefficient n_c=0.9 (reported in **Table 16**), and China ψ_G=0.95 for 2 story-buildings (for both *DL* and *LL*). However, the walls (as main contributor to the mass) in TAJ-18 are multiplied by a safety factor 1.1, so the effective reduction is just 1% (1.1·0.9 = 0.99). None of the codes add *LL* to the pitched roofs, therefore for the school the total DL and W_{tot} are the same, whereas the increase of *LL* related to the *DL* of the house ranges between +0.9% in Iran to +2.0% in China. This minimal addition does not change the overall division of masses which remains to be roughly 98% walls versus 2% diaphragms. To compare, a quick check of the weight implication of a rigid concrete slab (Nepalese values) resulted in an increase of nearly 18% for the house and 28% for the school, which proportionally increases the inertia forces.

Table 17. *Live Loads and distribution of seismic weights for the house and school designs.*

Country and Code for Loads and Actions		**Nepal** NBC 103-1994		**India** IS.875(p.2)-2007		**Pakistan** and BCP-SP-07 **Afghanistan** ABC-2012		**China** GB 50009-2012 JGJ 161-2008	
LL per floor or roof type	unit	C_{comb}	*LL*	C_{comb}	*LL*	C_{comb}	*LL*	ψ_c	*Q*
LL on first floor	kN/m²	0.3	2.0	0.25	2.0	0	2.0	0.5[3]	2.0
LL on verandah 1st floor	kN/m²	0.3	3.0	0.25	3.0	0	2.0	0.5[3]	2.0
Total seismic weight, W_{tot}	unit	*W*	%	*W*	%	*W*	%	G_{eq}	%
house, W_2 (5.35m+)	kN	367.9		367.9		360.6		338.1	
house, W_1 (2.75m+)	kN	736.2		732.7		700.8		679.5	
house, W_{tot}	kN	**1,104.1**	+1.9	**1,100.6**	+1.6	**1,061.4**	0.0	**1,017.6**	+2.9
house, W_{tot} [1]	%	=74.9		=74.6		=73.4		=72.0	
school, $W_1 = W_{tot}$ (2.95m+)	kN	**725.1**	0.0	**725.1**	0.0	**709.4**	0.0	**701.3**	0.0
school, W_{tot} [2]	%	=52.6		=52.6		=52.5		=52.9	
Country and Code for Loads and Actions		**Tajikistan** SNiP RT 20-01-2012		**Iran** NBRI-6 (2013)		**Turkey** TS-498 (1997)		**Croatia** EN 1991-1-1:2002	
LL per floor or roof type	unit	n_c	$LL \cdot \gamma_f$	C_{comb}	*LL*	n_c	*LL*	ψ_2	*LL*
LL on first floor	kN/m²	0.8	1.5·1.3	0.2	2.0	0.3[4]	2.0	0.3[4]	2.0
LL on verandah 1st floor	kN/m²	0.8	4.0·1.2	0.2	3.0	0.3[4]	2.0	0.3[4]	2.0
Total seismic weight, W_{tot}	unit	Q_k[5]	(η_i[6]· Q_k)	*W*	%	*W*	%	*W*	%
house, W_2 (5.35m+)	kN	374.3	501.6	375.6		424.1		375.8	
house, W_1 (2.75m+)	kN	793.6	547.6	746.6		853.6		747.8	
house, W_{tot}	kN	**1,167.9**	=89.8%[7]	**1,122.2**	+1.3	**1,277.7**	+1.4	**1,123.6**	+1.6
house, W_{tot} [1]	%	=73.5		=74.3		=74.2		=74.6	
school, $W_1 = W_{tot}$ (2.95m+)	kN	**907.0**	907.0	**738.8**	0.0	**847.1**	0.0	**737.3**	0.0
school, W_{tot} [2]	%	=52.7	=100%[7]	=52.4		=52.6		=52.6	

Note: The **bold** numbers mark the total seismic weight W_{tot} of the case study buildings
LL = *Q* = Characteristic value of (long-term) live load
$C_{comb} = \psi_c = n_c = \psi_2$ = Combination coefficient, and γ_f = safety factor
$W_{tot} = W = G_{eq} = \Sigma Q_k$ = Total seismic weight (expressed as *m* in tons in Europe and Turkey)
[1] Percentage of W_{tot} for the house compared to the total *DL* minus plinth (in Table 16)
[2] Percentage of W_{tot} for the school compared to the total *DL* minus plinth (in Table 16)
[3] ψ_c is (0.95·0.5) for 2-story buildings
[4] 0.3 for residential functions, for schools the combination coefficient is 0.6
[5] Q_k is the seismic weight at level *k*
[6] η_k is distribution factor at level *k* (for the first mode of vibration): $\eta_{2,house} = 1.34$, $\eta_{1,house} = 0.69$, $\eta_{1,school} = 1$
[7] Percentage of considered seismic weight in the first mode, $\eta_{tot,house} = 0.90$ and $\eta_{tot,school} = 1.0$

The seismic weights W_i (at *i*-th floor level) are conventionally lumped at the top of both buildings and first-floor level of the house. Some codes specifically describe the division of weights from the mid-levels of the story heights to the respective levels above and below (NEP-20, IND-16). For the house, the relation between W_2 and W_1 is almost exactly 1/3-2/3 for all countries. As the plinth is tightly packed with soil it is considered as part of the ground, thus level +0.0m starts at the top of this platform (**Figure 24**). The ground floor is not connected to the walls, and its loads are assumed to disappear directly into the ground. However, the bottom half of the ground floor walls is not considered in W_{tot}, meaning that for the house over 25% of the total *DL* (minus plinth) is not considered in the seismic weight, and for the school nearly 50%. The percentages in Tajikistan differ as the seismic weights are determined per each separate level (including safety factors), and then multiplied by a level distribution factor η_i. For these "simple" case study buildings, only the first mode of vibration needs to be

considered (explained in the next chapter), resulting in 10% reduction of the total considered seismic weight for the house ($\eta_{tot,house}$=0.90). Although the applied way of lumping masses just at floor levels (and exclusion of the plinth level) is a conventional and accepted approach for frame buildings that have a high ratio of mass located in the floors, the question rises whether this is an appropriate approach for heavy stone masonry buildings, where almost all mass is located in the walls. However, alternative approaches such as the distributed mass system and equivalent frame model are not suggested in any of the codes. Such possibly more suitable concepts will be addressed in follow-up papers, at the validation stages of the overall research.

5.4 Seismic Base Shear for Ultimate Limit State

This section analyzes and compares Equivalent Lateral Force methods and corresponding base shear formulas of selected codes, to be used for calculation of the Ultimate Limit State seismic demand of the rubble stone masonry house and school. The analyses aim to determine which code or country is the most tolerant or most conservative toward this technique. In the spirit of "non-engineered seismic design", the focus is on a simplified approach performed by hand calculations, wherever possible.

5.4.1 Performance Objectives and Limit States

To design and validate structures, most modern codes define seismic performance objectives and impose a form of limit states design for the verification of structural elements. Performance objectives are defined as the relation between the expected seismic hazard (earthquake design level) and the acceptable damage (building performance level, or limit state). Recommended design levels are for "frequent, occasional, rare and very rare earthquakes", based on probability of exceedance during the lifetime of the building and/or recurrence intervals, whereas recommended performance levels are generally divided into "fully operational, operational, life-safety and near collapse" (Vision 2000 Committee, 1995). Two important limit states are: i) Serviceability Limit State (SLS) for light but frequently occurring earthquakes with a no-damage objective. It requires that a structure remains in its elastic phase without any residual displacement after being subjected to earthquake action, and is mainly concerned with limitation of stresses and displacements; and in the case of masonry with avoidance of cracking. SLS is usually expressed as a fraction of the ULS, for instance 20% in NEP-20 and 35% in the Chinese National seismic code CN-GB. However, due to the regularity, heavy mass and high in-plan stiffness of the box-type designs of the case study buildings, and provided that the mortar is of acceptable quality, it is expected that SLS-verifications are not governing in seismic design of stone masonry buildings. ii) Ultimate Limit State (ULS) for severe but less often occurring seismic events, either allowing damage or preventing collapse. The ULS-verification considers the non-linear resources of materials and relies on the strength, ductility and energy dissipation characteristics of the structural elements. For stone masonry, it mainly deals with strength design properties such as compression, tension, flexure and shear, with the basic restriction that, for each internal action, the seismic demand does not exceed the ultimate capacity. The immediate attention of this chapter is on ULS and the primary performance level of life-safety. In EC8 this is referred to as a no-collapse requirement, whereas the US-based codes (PAK-07, AFG-12, ASC) refer to comparable Strength Design procedures and define a "reliability objective" that must meet certain Strength Limit States. Pakistan and India have not (clearly) defined any objective, whereas IRN-15 relates three levels of allowable damage to the importance of the structure.

5.4.2 Reference Earthquake Design Level

The following reference for comparing the ULS-verification methods is taken: "The rare earthquake event" that is characterized by a 10% probability of exceedance within 50 years of service life of the structure (10%PE_{50y}), or a 475-year return period (RP_{475}), such as clearly defined in NEP-20, PAK-07, CN-JGJ, IRN-15, TUR-18 and EC8. Afghanistan, following ASC-10, takes the Maximum Considered Earthquake (MCE) for 0.2s spectral response acceleration as the starting point (2%PE_{50y}). The mapped MCE values are then scaled down by two-thirds, which represents a close approximation of the life-safety design level of 10%PE_{50y} (Leyendecker et al, 2000). IND-16 has a similar approach but defines the design earthquake as 50% of the maximum credible earthquake level, by introducing a reduced seismic zonation factor (Z/2). However, the Indian seismic intensities are not based on probabilistic hazard analyses but were assigned empirically, based on "likely intensity" and "engineering judgement" (…) "therefore, it is not possible to assign a probability of occurrence to these levels" (Jain, 2003; Jain and Rai, 2019). The design earthquake levels in TAJ-18 are also not based on a probabilistic approach, but on the MSK-64 intensity scale (Medvedev and Sponheuer, 1969). China, who was one of the first countries to introduce performance objectives in their 1989 seismic code (GBJ 11-89, 1993), has defined three "basic seismic precautionary levels". The national code CN-GB takes the first no-damage requirement under frequent earthquakes (63%PE_{50y} or RP_{50}, which is similar to the operational objective with SLS-verification), as their main design earthquake level "unless stated differently". Such is the case for stone masonry in rural code CN-JGJ, which dictates the second design level with the objective of repairable damage under "precautionary-level" earthquakes (10%PE_{50y} or RP_{475}). The naming of "precautionary and rare (third-level)" in China is somewhat confusing as all other countries refer to these as "rare and very rare". All objectives (if clearly defined in the codes) and earthquake design levels are shown in **Table 18**.

Table 18. *Relation between performance objectives, earthquake design levels and method of analysis for Ultimate Limit State verifications of the rubble stone masonry case study buildings.*

Country	Performance obj.	Earthq. design level	Method	Conditions and structural requirements
NEP-20	Life-safety	RP_{475} (Level E1)	ELF	$H < 15$m and $T_1 < 0.5$s (schools not recomm.)
IND-16		DBE is 1/2 of MCE	ELF Modal	$H < 15$m, seismic zone II (schools n.a.) All buildings in zones III-V (schools n.a.)
PAK-07!		10%PE_{50y}	S-ELF	$H \leq 2$ stories in occupancy cat.4 (but n.a.)
AFG-12!	Reliability checks	2/3·MCE for 2%PE_{50y}	S-ELF ELF Modal	Risk cat.II (house) ≤ 3 st. = n.n. ($SDC_{C\text{-}F}$ = n.a.) Risk cat.III (school) for SDC_B (SDC_C = n.a.) Risk cat.III (school) for $SDC_{D\text{-}F}$ (but n.a.)
CN-GB! CN-JGJ	No damage Repairable damage	63%PE_{50y} or RP_{50} 10%PE_{50y} or RP_{475}	Modal ELF	For flexible diaphragms $H \leq 2$ stories, flexible diaphragms allowed
TAJ-18	Life-safety	MSK-64 intensity scale	S-Modal	Only first mode, for $H \leq 5$ stories and $T_i < 0.4$s
IRN-15	Based on importance	10%PE_{50y} or RP_{475}	ELF	For masonry buildings n.n.
TUR-18!	Life-safety	10%PE_{50y}	Modal	For flexible diaphragms
EC8	No-collapse	10%PE_{50y} or RP_{475}	ELF Modal	Imp. class II (house) and "simple" (but n.n.) Imp. class III (school), for flexible diaphragms

!	= Rubble stone masonry not allowed in seismic areas	H	= Height of the building
ELF	= Equivalent Static, or Equivalent Lateral Force method	T_1, T_i	= Fundamental period of vibration
S-ELF	= Simplified Equivalent Lateral Force method	n.n.	= No verification needed
Modal	= Dynamic analysis or Modal Response Spectrum method	n.a.	= Not allowed for rubble stone mas.
S-Modal	= Simplified Modal analysis for first mode of vibration	SDC	= Seismic Design Category

5.4.3 Seismic Analysis Methods

Types of seismic analysis include linear (elastic) methods such as the Equivalent Lateral Force method (ELF, static) and the Modal Response Spectrum method (dynamic), as well as non-linear (inelastic) methods like the Pushover analysis (static) and Time-History procedure (dynamic). The modal or response spectrum method considers the dynamic response and modes of vibration by analyzing the structure as a multi-degree-of-freedom system, where the mass of the structure is lumped at its nodes and where the displacements and rotations of these nodes completely define the deformed configuration of the structure. A sufficient number of modes must be included to activate a minimum percentage of the total seismic mass in the horizontal direction under consideration, which is set at 85% in CN-GB and at 90% in all other codes. However, for buildings that conform to certain rules of uniformity and height restrictions, it is assumed that these percentages are reached after the first mode of vibration, and that the higher modes of vibration which complement the total response of the structure may be neglected. In the spirit of "non-engineered seismic design", the focus in this chapter lies on the static linear procedure and the ELF method in particular, which idealizes the structure as a single-degree-of-freedom system with its total mass oscillating as one at its fundamental period of vibration. It substitutes the earthquake ground motion with external static horizontal forces (hence the term "equivalent") that amount to the base shear force. Generally, masses are lumped at each floor level, and the story forces are used to determine the displacements and internal forces in the structure. ELF computes the maximum base shear for the seismic weight of a structure, as determined in the previous sections for the case study buildings.

A first major condition for application of ELF in all codes, is that buildings must be regular in both plan and elevation. For both case study buildings these conditions are met (previous section). Further requirements are added to **Table 18**, including maximum allowed heights of structures (H between 2-5 stories), maximum values for the Natural Period of Vibration (T around 0.4-0.5s), the building importance, and seismic zoning. Pakistan introduces a Simplified ELF (S-ELF) method for buildings with $H \leq 2$ in occupancy category 4, which applies to both the house and the school design. AFG-12 also recognizes both ELF and S-ELF but relates the method of analysis to a seismic design category (SDC), as defined by different levels of design accelerations in combination with a risk category. The school (category III) qualifies for ELF in SDC_B (approx.< 0.13g), whereas the house (category II) is exempt from seismic analysis in $SDC_{A\text{-}B}$. Both case studies are not permitted in $SDC_{C\text{-}F}$ which prohibits ordinary and detailed plain masonry shear walls. EC8 has a similar approach, where the house (importance class-II) conforms to a list of requirements for material strengths, dimensions, reinforcements and minimum percentages of cross-sectional area of shear wall, and therefore can be marked as a "simple masonry structure" for which no verification is needed. The school (class-III) however requires modeling because of the flexible diaphragm. Turkey and China (CN-GB) also demand dynamic analysis for flexible diaphragms, whereas CN-JGJ allows ELF for buildings with $H \leq 2$ regardless of the type of floor and roof. India has the strictest code by allowing ELF only for buildings with $H < 15$m and $T < 0.4$s in the lowest seismic zone II (design acceleration $Z/2 \leq 0.05$g). However, their seismic code for low-strength masonry (IS:13828-1993, 2018) requires no special provisions in zone II, effectively meaning that rubble stone masonry houses (schools are prohibited in any case) must be dynamically modeled in zones III-IV (although not recommended in IV and prohibited in V). Iran on the other hand does not require any form of analysis for URM (or CM) whatsoever. Lastly, the Russian-based codes require Modal analysis (called spectral method) for all structures, where the seismic weight at each level is multiplied by a level distribution factor η_{ik}, which takes into account the displacements at the different floor levels for different modes of vibration.

However, for simple buildings ($H \leq 5$ and $T_i < 0.4$s, TAJ-18), a simplified formula (S-Modal) is given which only considers the first mode and where $\eta_{1,k}$ is directly related to the building height. In this respect the S-Modal analysis closely approximates the ELF method, with the main difference that S-Modal includes a reduced portion of the total seismic weight.

Some caution is observed. As ELF computes the maximum base shear, this method tends to overestimate the base shear for short-period buildings due to the inclusion of the full seismic weight, as opposed to the response spectrum modal analysis which combines the effective weights of all modes, of which the first-mode effective weight typically amounts to 60-80% of the total seismic weight (Villaverde, 2009). For modal analyses, most codes dictate a minimum of 85-90% of activated mass, or demand validation with inclusion of at least three modes (TAJ-18, IRN-15). For masonry, Priestly et al (2007) recommend the inclusion of 90% of effective (or equivalent) seismic weight, which is in line with the S-Modal method in Tajikistan, where 89.8% of the seismic weight is considered for the house (**Table 2**). Since the generation of earthquake inertia forces is proportional to mass, risk of overestimation will be of major influence on the heavy stone masonry buildings.

5.4.4 Base Shear Formulas for the ELF Method

Given the simplicity and regularity of the two case study buildings, it is assumed that both house and school designs qualify for either ELF, S-ELF, or comparable approaches such as S-Modal in all countries. Base shear is the maximum lateral force, expected to occur at the base of a structure due to seismic motions. All codes present the base shear formulas in terms of a seismic acceleration coefficient, applied in the center of mass of the structure and defined as a fraction of the gravity acceleration (g), to be multiplied by the total seismic weight of the structure (W_{tot}). Most formulas are structured (or can be restructured) similarly and express the base shear as a function of the spectral acceleration, to be reduced by a structural behavior factor. The spectral acceleration results from the peak ground acceleration at bedrock ($PGA_{bedrock}$), that is first amplified by the overlaying soil conditions (peak ground acceleration at surface level = $PGA_{surface}$), and then further modified by the structure in relation to its fundamental period of vibration T. The spectral acceleration is plotted in an elastic (unreduced) response spectrum as a function of T and for a given site profile; in the upcoming comparisons rock is taken as the reference soil. The elastic response spectrum is then reduced by the structural behavior factor that in general accounts for the inherent inelastic properties of the lateral-resisting structural system such as ductility, overstrength and energy dissipation, although for stone masonry these are expected to be minimal. Most codes refer to this as the design response spectrum, but to avoid confusion of terminology, this thesis chapter refers to "reduced (inelastic) response spectrum" (versus unreduced (elastic) response spectrum). The base shear may be further increased due to the importance of the structure. This leads to the following conceptual representation of base shear for ULS-verifications:

$$Conceptual\ base\ shear = \frac{(PGA_{bedrock} \cdot soil) \cdot spectral\ amplification}{structural\ behavior} \cdot importance \cdot seismic\ weight$$

where $(PGA_{bedrock} \cdot soil) \cdot spectral\ amplification = spectral\ acceleration$

and $PGA = PGA_{bedrock}$ or $PGA = (PGA_{bedrock} \cdot soil) = PGA_{surface}$

depending on how each code provides the seismic hazard.

All original base shear formulas and base shear coefficients for both ELF and S-ELF are shown in the first column of **Table 19**, which are then combined and conceptually rewritten in the second column. The last column shows additional requirements or restrictions, such as minimum and maximum limitations of the base shear. Since S-Modal considers only the first mode, it qualifies for the conceptual rewrite with the notion that the seismic weight (Q_{tot}) is not fully included (for the house), by introducing the combined effect with the level distribution factors ($\eta_k \cdot Q_k$) as an additional constant ($\eta_{tot,house} = 0.90$ and $\eta_{tot,school} = 1.0$, **Table 17**). Although the US-based formula of AFG-12 is not related to PGA (by using the full spectral acceleration based on different parameters), it can still be rewritten in such way that it very closely approximates the life-safety design level of 10%PE_{50y}, as explained previously. The spectral acceleration in TUR-18 (which largely follows ASC-16) also matches this approximation. However, this formula is the only one that cannot be rewritten into the conceptual format, as it does not have a constant-ordinate plateau (between T_A and T_B) in the reduced response spectrum, since the Turkish seismic load reduction factor $R_a(T)$ considers a linear dependence on variable T/T_B toward T_B. The Chinese codes differ by combining all the functions related to seismic hazard and structural behavior into one single coefficient α, which are lower for SLS-verifications (CN-GB) and higher for ULS-verifications (CN-JGJ, included in **Table 19**).

All differences as described above are further explained in the next sections, which compare each of the base shear factors separately. For each formula it is aimed to extract the design peak ground acceleration, simply referred to as PGA, at either bedrock level ($PGA_{bedrock}$) or ground surface level ($PGA_{surface}$), depending on how this design value is provided by the codes. By doing so, it is possible to compare the effects on a particular structure due to the ground conditions and structural characteristics as dictated by each national code, for any given hazard at site. All relevant values and coefficients that are used for the comparisons in the next sections, are added to **Table 22**.

5.4.5 Soil Conditions

Local soil conditions have a significant influence on the PGA and shape of the response spectra. Bedrock represents the reference conditions, whereas overlaying soil layers may cause amplification effects. Soft soils generally have a higher amplifying effect on the ground motions than stiff and hard soils (Villaverde, 2009). First, the reference soil type for the upcoming calculations is determined. The codes distinguish several parameters for soil classification, of which the "average shear-wave velocity in the upper 30m ($v_{s,30}$ in m/s)" is most recommended (PAK-07, CN-GB, IRN-15, TUR-18, EC8). Nepal and India distinguish 4 soil classes by using different parameters. Nepal expresses hard rock and stiff soils (type A) in terms of "unconfined compressive strength (in kPa)" and divides soft soils (type C) by "standard penetration test values (N_{SPT} in blows/30cm)" or by "representative undrained shear strength (s_u in kPa)", whereas IND-16 defines the bearing capacity of all subsoils in terms of N_{SPT}. However, these distinctions are less relevant, as the response spectra for short-period buildings in Nepal and India are similar for soil types A-C, whereas construction on weak soils (type D) "should be avoided". Soil type C roughly resembles soil profile S_D (PAK-07), class D and ZD (AFG-12, TUR-18), site category III (CN-GB, IRN-15, TAJ-18) and ground type C (EC8) with $v_{s,30}$ around 150-180m/s. Depending on seismic zone or structural typology, the $PGA_{bedrock}$ values are amplified by a separate soil adjustment factor ranging from $S = 1.15$ (EC8) to as high as $F_a = 1.6$ (AFG), whereas the soil effects in Nepal, India, Tajikistan and Iran are directly combined into $PGA_{surface}$, and in China directly into PGA.

Table 19. *Conceptual base shear formulas combined with seismic coefficients, for ULS-verification.*

Country	Base Shear Formulas & Base Shear Coefficients	Combined and re-written for ULS verification	Requirements and restrictions
NEP-20	$V = C_d(T_1)\cdot W$ $C_d(T_1) = C(T_1)/(R_\mu \cdot \Omega_u)$	$V = \frac{Z\cdot C_h(T_1)}{R_\mu \cdot \Omega_u}\cdot I\cdot W$	$C(T_1) = C_h(T_1)\cdot Z\cdot I$
IND-16	$V_B = A_h \cdot W$ $A_h = ((Z/2)\cdot(S_a/g))/(R/I)$	$V_B = \frac{(Z/2)\cdot(S_a/g)}{R}\cdot I\cdot W$	$V_{B(\min)} > \rho\cdot V_B$ ρ is % related to seismic zone
PAK-07 (S-ELF)		$V = \frac{C_a\cdot 3.0}{R}\cdot W$	20% more conservative than ELF with spectral acceleration $C_a\cdot 2.5$
AFG (ELF)	$V = C_S\cdot W$ $C_s = (S_{DS}/(R/I_e))\cdot W$	$V = \frac{\frac{2}{3}\cdot S_S\cdot F_a}{R}\cdot I_e\cdot W$	$S_{DS} = \frac{2}{3}\cdot S_{MS}$ and $S_{MS} = F_a\cdot S_S$ $C_s > 0.044\cdot S_{DS}\cdot I_e \geq 0.01$
AFG (S-ELF)	$V = ((F\cdot S_{DS})/R)\cdot W$	$V = \frac{\frac{2}{3}\cdot S_S\cdot F_a\cdot F}{R}\cdot W$	$S_{DS} = \frac{2}{3}\cdot F_a\cdot S_S$ F = 1.0 for 1 story and 1.1 for 2 st.
CN-JGJ		$F_{Ekb} = \alpha_{\max b}\cdot G_{eq}$	All factors are combined in $\alpha_{\max b}$
TAJ-18 (S-Modal)	$S_{ik} = K_1\cdot K_2\cdot K_3\cdot S_{oik}$ $S_{oik} = Q_k\cdot A\cdot \beta_i\cdot K_\psi\cdot \eta_{ik}$	$S_{ik} = \frac{A\cdot\beta_i\cdot K_3}{1/(K_2\cdot K_\psi)}\cdot K_1\cdot\eta_{ik}\cdot Q_k$	$\eta_{ik} = \frac{x_k\cdot\sum_{j=1}^{n} Q_j\cdot x_j}{\sum_{j=1}^{n} Q_j\cdot x_j^2}$ for i=1
IRN-15	$V_u = C\cdot W$ $C = (A\cdot B\cdot I)/R_u$	$V_u = \frac{A\cdot B}{R_u}\cdot I\cdot W$	$V_{u,\min} = 0.12\cdot A\cdot I\cdot W$
TUR-18	$V_{tE}^{(X)} = S_{aR}(T_p^{(X)})\cdot m_t$ $S_{aR}(T) = S_{ae}(T)/R_a(T)$	(1) $V_{tE}^{(X)} = \frac{S_S\cdot F_S}{R}\cdot I\cdot W_t$ (2) $V_{tE}^{(X)} = \frac{S_S\cdot F_S}{D+(R/I-D)\cdot T/T_B}\cdot W_t$	$S_{ae}(T) = S_{DS} = S_S\cdot F_S$, $m_t = W_t/g$ (1) formula with $R_a(T)$ for $T_1 > T_B$ (2) formula with $R_a(T)$ for $T_1 \leq T_B$ $V_{tE}^{(X)} \geq 0.04\cdot m_t\cdot I\cdot S_{DS}\cdot g$
EC8	$F_b = S_d(T_1)\cdot m\cdot\lambda$ $S_d(T_1) = (a_g\cdot S\cdot 2.5)/q$ or $S_d(T_1) = a_{gR}\cdot S\cdot\left[\frac{2}{3}+\frac{T}{T_B}\cdot\left(\frac{2.5}{q}-\frac{2}{3}\right)\right]$	(1) $F_b = \frac{a_{gR}\cdot S\cdot 2.5}{q}\cdot\gamma_I\cdot W$ (2) $F_b = a_{gR}\cdot S\cdot\left[\frac{2}{3}+\frac{T}{T_B}\cdot\left(\frac{2.5}{q}-\frac{2}{3}\right)\right]\cdot\gamma_I\cdot W$	$a_g = \gamma_I\cdot a_{gR}$ and $m = W/g$ λ is correction factor = 1.0 ($\leq$ 2 st.) (1) for 0.15s < T_1 < 0.4s (2) for T_1 < 0.15s

$V = V_B = F_{Ekb} = V_u = V_{tE}^{(X)} = F_b$	Total horizontal lateral force or total design seismic base shear
$C_d(T_1) = A_h = C_s = C = \alpha_{maxb} = S_{aR}(T) = S_d(T_1)$	Design horizontal seismic response coefficient or design spectrum
$C(T_1)$ and $S_{ae}(T)$	Horizontal elastic design spectral acceleration
S_{ik} and S_{oik}	Lateral seismic force and coefficient, for mode i at level k
$Z = Z/2 = C_a = A$	Seismic zone factor or design base acceleration ($PGA_{surface}$[2])
a_g and a_{gR}	Design and Reference PGA on type A ground ($PGA_{bedrock}$[1])
S_S and S_{DS}	Design spectral response accel.: mapped and for short periods[3]
S_{MS}	Spectral response acceleration parameter for MCE[3]
$F_a = F_s = S$	Soil factor
$C_h(T_1) = S_a/g = 3.0 = \beta_i = B = 2.5$	Spectral amplification coefficient, or spectral shape factor
$F = K_3$	Coefficient considering number of stories or height of the structure
$R_\mu = R = R_u = q$	Behavior factor, e.g. response reduction or ductility factor
K_2 and K_ψ	Coefficients considering the structural type and energy dissipation
$R_a(T)$	Seismic load reduction coefficient
$\Omega_u = D$	Overstrength factor
T and T_B	Natural period of vibration, and control point on response spectrum
$I = I_e = K_1 = \lambda_I$	Importance factor
η_{ik} and x_j or x_k	Level distribution factor for mode i at level k, and heights at level j,k
$W = W_t = G_{eq} = Q_k = m_t = m$	Seismic weight, or equiv. total of gravity loads or mass of structure
Q_j or Q_k	Seismic weight of the building assigned to level j or k

Notes: [1] Some codes provide accelerations times mass (in g), whereas [2] (most) other codes provide a dimensionless seismic coefficient (as a fraction of g) or [3] a dimensionless spectral acceleration coefficient, multiplied by the weight.

As the limits of softer and weaker soils cannot be fully aligned, rock soil with $v_{s,30}$ around 750-800m/s is taken as the reference condition for fair comparison of the base shears. These are types A (NEP-16, IND-16, EC8), category I_0 (CN-GB), category I (IRN-15, TAJ-18), soil profile S_B (PAK-07) and class B (AFG-12), which all have a soil factor of 1.0. However, following the latest revision in ASC-16, the Turkish soil factor F_s for class ZB is reduced to 0.9. Tajikistan relates the soil effects to the design seismic intensity as given for different seismic zones (without an additional soil factor), in China the soil effects are adjusted within the design seismic coefficient α, and in Iran the soil factor S is directly linked to the spectral amplification; all further explained in the next sections. Lastly, it is realized that rocky ground is a best-case scenario, but the fact that most rubble stone masonry takes place in mountainous areas, does not necessarily mean that all sites have favorable soil conditions. For instance, Kathmandu Valley is highly susceptible to basin effects, site amplification and liquefaction potential (Tallett-Williams et al, 2016). Therefore, local soil conditions must always be considered on a case-to-case basis.

5.4.6 Design Peak Ground Acceleration

The intensity of expected ground motion at a given site (site hazard) is expressed in terms of a design peak ground acceleration (PGA), which in most codes is either defined as $PGA_{bedrock}$ or $PGA_{surface}$, and in US-based codes as the full spectral acceleration. The earthquake design levels are stipulated by the codes either through set values of PGA that correspond to designated seismic zonation, by interpolation of seismic hazard contour maps, or by site-specific tabulation of coordinates. This section compares the PGA values for ULS-verification on rock soil for each country. All seismic zones and corresponding PGA are shown in **Table 20**, which is further combined with the required verification methods (and restrictions) for both the house and school designs (**Table 18**). NEP-20 assigns a seismic zoning factor (Z) to selected main locations, or else Z must be determined by approximate interpolation between the contour lines of the seismic zoning map. IND-16, PAK-07 and IRN-15 directly assign a design coefficient ($Z/2$, C_a and A, respectively) to each seismic zone as drawn on their zonation maps. Pakistan adds a near-source factor ($N_a = 1.1$) for all sites, but only in the highest seismic zone 4. In most Russian-based codes the PGA values are assigned to seismic intensity zones where soil category II is taken as the reference. For instance, intensity zone 9 represents $A = 0.40$g (TAJ-18). However, on rock soil (category I) it is permitted to use the design values of one intensity level less, so that zone 9 becomes zone 8 with $A = 0.20$g. Effectively it means that on rock soil, the base shear is reduced by half.

AFG-12 (following ASC-10) maps the complete short-period spectral acceleration for the very rare earthquake event ($S_S \cdot F_a$ at $2\%PE_{50y}$) on rock soil ($F_a = 1.0$), which needs to be reduced to the design level ($S_{DS} = 2/3 \cdot S_S$ at ~$10\%PE_{50y}$). Set limitations of the design values correspond with an SDC which defines the method of analysis. To transform these set values into representative PGA levels (although not utilized as such in the US-based approach), they are to be divided by the spectral amplification ($S_{DS}/2.5$), which is a close and acceptable approximation for initial design purposes (Leyendecker et al, 2000). TUR-18 also accepts PGA = $S_{DS}/2.5$ and has adopted a system of site-specific hazard coordinates, which includes spectral acceleration (as well as PGA) values for $10\%PE_{50y}$. The Chinese seismic zonation parameter map (GB 18306-2015, 2016) assigns a level of "seismic fortification intensity" (6-9) to all administrative districts based on local seismic hazard, site profiles and near-fault conditions. This intensity is coupled with three sets of seismic coefficients (α_{max}), of which the rural code CN-JGJ requires the precautionary (second) level ($10\%PE_{50y}$). These values are 2.8 times higher than for frequent earthquakes in CN-GB ($63\%PE_{50y}$ = SLS) and can be easily translated to PGA by

dividing the maximum acceleration coefficient with the spectral amplification (= $0.45 \cdot \alpha_{maxb}$, see next sections). EC8 recommends "unreinforced masonry (URM) that satisfies prescribed provisions" only in areas with $PGA_{bedrock} = a_{g,urm} \leq 0.20g$. However, CRO-11 has set no limitation, but requires dynamic modeling for schools (always) and houses for $a_{g,urm} > 0.30g$.

Table 20. *Relation between seismic zones, design peak ground accelerations and allowed methods of analysis for houses and schools on rock soil.*

	NEP-20[1]			**IND-16**[2]			**PAK-07**[!]			**AFG-12**[!]			**CN-JGJ**		
PGA	zone	Z	an.	zone	$Z/2$	an.	zone	C_a	an.	SDC	$S_{DS}/2.5$	an.	fort.	$0.45 \cdot \alpha_{max}$	an.
0.05				II	0.05	n.n.							6	0.05	ELF
0.10				[3]III	0.08	dyn.	1	0.075	n.a.				7	0.10	ELF
0.15				IV	0.12	n.r.	2a	0.15	n.a.	B	0.13	n.n.	[4]7	0.15	ELF
0.20				V	0.18	n.a	2b	0.20	n.a.	C	0.20	n.n.	8	0.20	n.a.
0.25	1	0.25	ELF							D	0.25	n.a.			
0.30	2	0.30	ELF				3	0.30	n.a.	D	0.30	n.a.	8	0.30	n.a.
0.35	3	0.35	ELF												
0.40	4	0.40	ELF				[5]4	0.40	n.a.	D	0.40	n.a.	9	0.40	n.a.
	TAJ-18			**KYR-18**[!]			**IRN-15**			**TUR-18**[!7]			**CRO-11**[7]		
PGA	int.	A	an.	int.	a_{gR}	an.	zone	A	an.	DTS	$S_{DS}/2.5$	an.		$a_{g,urm}$	an.
0.05	6		n.n.	7	0.05	n.a.							v.low	[8]0.06	n.n.
0.10	7	0.10	s.mod		~								low	[8]0.12	[9]n.n.
0.15					~					4	0.13	n.a.		~	
0.20	8	0.20	s.mod	8	0.20	n.a.	low	0.20	n.n.		~	n.a.		~	n.n.
0.25					~		mod.	0.25	n.n.	3	0.25	n.a.		~	
0.30					~		high	0.30	n.n.	2	0.30	n.a.		[8]0.30	dyn.
0.35					~		v.high	0.35	n.n.	1	0.35	n.a.		~	dyn.
0.40	(9	0.40)	[6]n.n.	9	≥0.40	n.a.					~	n.a.		0.38	dyn.
0.50				(>9	≥0.60)	n.a.				1	≥0.50	n.a.			

SDC = DTS = Seismic design category
fort. = Fortification level; int. = Seismic intensity level
$Z = Z/2 = C_a = S_{DS}/2.5 = 0.45 \cdot \alpha_{max} = A = PGA_{design}$
$a_{g,urm}$ = $PGA_{bedrock}$ for unreinforced masonry
an. = Method of analysis
ELF = Equivalent lateral force method
dyn. = Dynamic modeling
s.mod = Simplified modal method
n.n. = Analysis not needed
! = n.a. = Rubble stone masonry not allowed

n.r. = Rubble stone masonry not recommended
[1] Schools allowed, but approval needed
[2] Schools not allowed in rubble stone masonry
[3] Maximum allowed zone
[4] Maximum allowed zone but max. 1 story height;
[5] To be multiplied with near-fault factor N_a
[6] Not applicable on rock soil
[7] Dynamic modeling always, for flexible diaphragms
[8] EC8 recommends $a_{g,urm}$<0.05g; <0.10g and <0.20g
[9] Dynamic modeling for schools, for $a_{g,urm}$>0.12g

To make any further differences visual, seismic hazard maps for the rare earthquake event on rock soil are combined for South and Central Asia (**Figures 25A, 25B**), and for the Caucasus and Middle East (**Figures 26A, 26B**). Disputed border areas are "assigned" to the country that currently administers the region. The 0.2s spectral acceleration map in AFG-12 is taken from Boyd et al (2007), which also contains the $10\%PE_{50y}$ hazard map as included here, although the report notes that the hazard values are relatively uncertain due to missing information. The preliminary map for Bhutan ($10\%PE_{50y}$, Goda et al, 2019) highlights the relatively low design values in India compared to Nepal, Bhutan and

Pakistan. However, the Chinese PGA values (separate map for 10%PE_{50y} in GB 18306-2015, 2016) on the other side of the Himalayan range are more in line with the Indian values of 0.12-0.18g bordering Kashmir. In Tajikistan the maximum design values are also relatively low, as these are halved on rock soil. This differs highly with the seismic map of Kyrgyzstan (SN KR 20-02:2018, 2018), which on rock soil (S = 1.0) contains values > 0.60g (added to **Table 20**). For the same reason, Iranian values are much higher around the borders with Turkmenistan (SNT 2.01.08-99, 2000). The halved acceleration values in Georgia (based on MSK-64, PN 01.01-09, 2012) bordering the Greater Caucasus Range match closely with the halved values on the Russian map OCR-2015-A (10%PE_{50y}, SP 14.13330.2018, 2018), bearing in mind that for school buildings Russia dictates a stricter map (5%PE_{50y}, OCR-2015-B). On the other borders larger differences are noted between Georgia, Azerbaijan (MSK-64, soil factor K_q = 0.7, AzDTN 2.3-1, 2014) and Armenia (10%PE_{50y}, K_0 = 0.8, RABC 20.04_, 2020). Turkey is no longer subdivided into seismic zones but has adopted a system of site-specific hazard coordinates, of which the map in **Figure 26B** is a representation of the Turkish gradient map (10%PE_{50y}, Decree BKK-2018/11275, 2018). Lastly, EC8 does not contain hazard maps as these must be provided by the partnering countries in their national annexes.

Both table and map show that India uses much lower design values than its neighboring countries, where $Z/2$ = 0.18g for the highest zone V is still lower than the lowest zone 1 in Nepal at Z = 0.25g. The map further shows a relative lack of detailed zoning in India; both these concerns have been expressed in several papers over the years, such as Bhatia et al (2009), Ghosh et al (2012). Stone masonry is still practiced in the Northeastern regions (NE, fully assigned to zone V) and Northwestern regions (NW, zones V-IV; the latter with $Z/2$ = 0.12g). Recent probabilistic seismic hazard analyses (PSHA) in the NE present PGA values (10%PE_{50y}, zone V) ranging between 0.27-0.49g for various locations in Assam (Bahuguna and Sil, 2018) and 0.18-0.60g in Manipur (Pallav et al, 2012). In zone IV values reach as high as 0.71g near Darjeeling (Maiti et al, 2016), whereas Das et al (2016) estimate values not higher than 0.32g anywhere in these regions. PSHA in the NW results in PGA around 0.6-0.75g in the states of Uttarakhand, Himachal Pradesh and Kashmir (Mahajan et al, 2010), opposed to Rout et al (2015) in which no value exceeds 0.36g for the same locations. Overall, large differences are observed between these studies, but they have one thing in common: All values of PGA are significantly higher than the design value of $Z/2$ = 0.18g in the Indian code. On the other hand, it must be noted that these low values are adjusted by introducing a relatively high seismic load combination factor of 1.5, making the seismic effects in India among the highest of all (explained further on).

High variations are also seen between studies for all other countries (for instance around the borders of Tibet, Rahman et al, 2017), which indicates a substantial uncertainty in hazard estimation. Differences are caused by the many parameters that are required to develop hazard maps, which introduce a high range of assumptions about earthquake source locations, recurrences and magnitudes, for which detailed historical data are often lacking or incomplete in these regions (Stein et al, 2018). They further question the need for a too detailed map which may undervalue the risk, as for instance the whole country of Nepal may be prone to larger earthquake than those from the past. Therefore, they propose just one uniform hazard level for Nepal based on large earthquakes with long return periods.

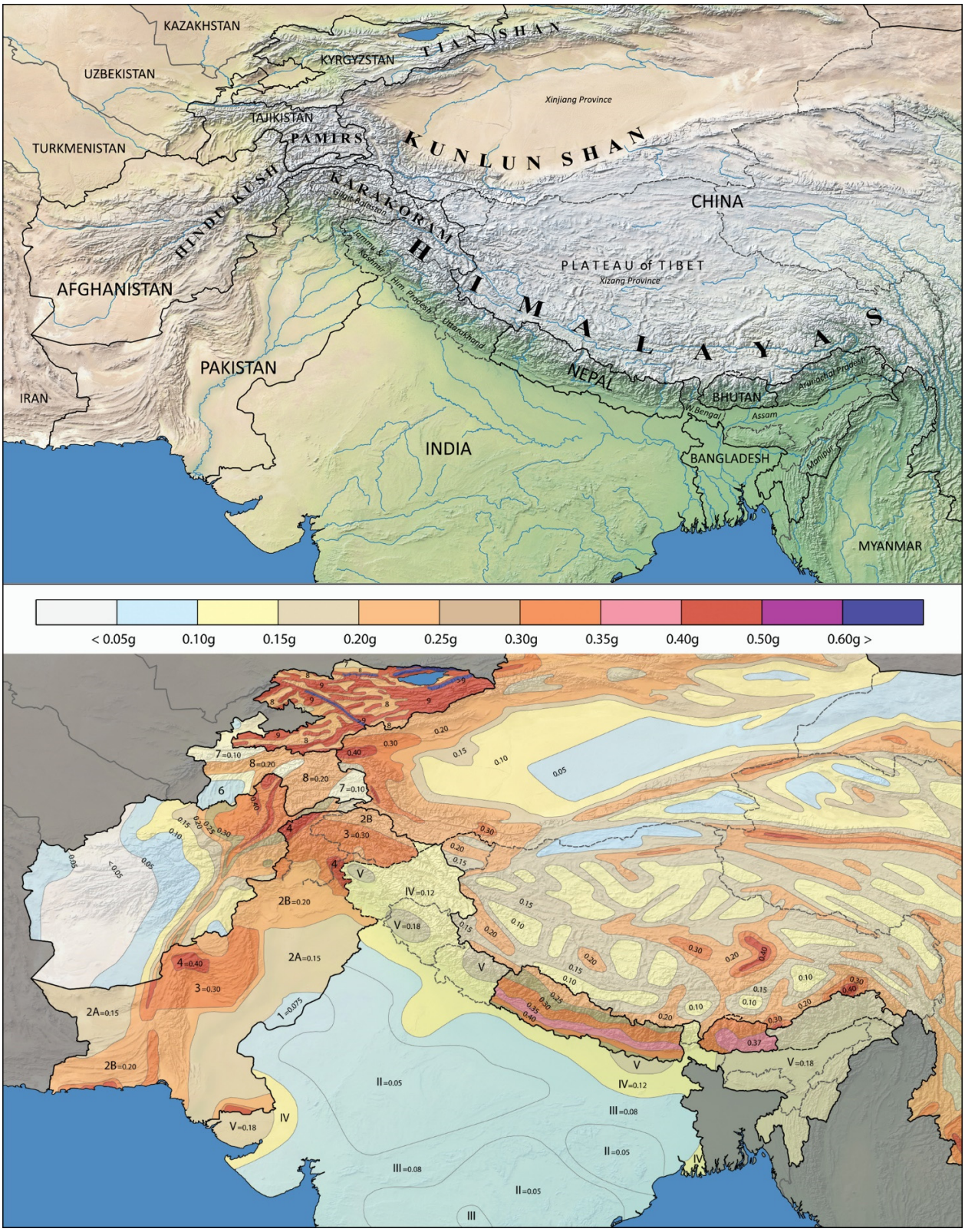


Figure 25. (A) *Mountain ranges of South and Central Asia (original source: Natural Earth raster + vector map) and* ***(B)*** *Effective design peak ground acceleration values on rock soil in these regions.*

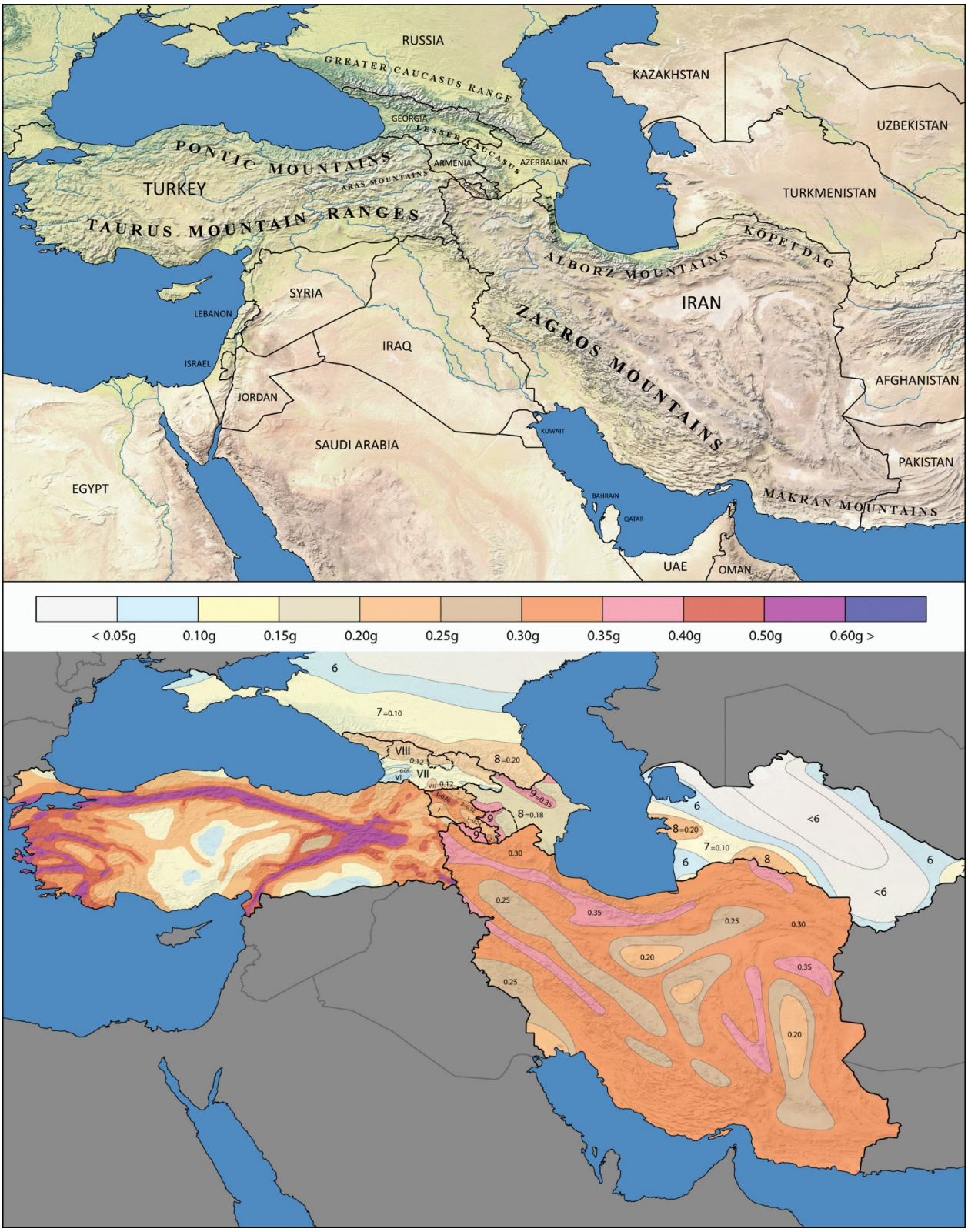


Figure 26. (C) *Mountain ranges of the Caucasus and the Middle East (original source: Natural Earth raster + vector map) and* ***(D)*** *Effective design peak ground acceleration values on rock soil in these regions.*

5.4.7 Natural Period of Vibration

The spectral acceleration on a structure mainly depends on its fundamental (or natural) period of vibration T_1 (in seconds). Main parameters affecting T_1 are the weight and height of the building, as well as the stiffness of the lateral-resisting elements in relation to their distribution in plan and elevation within the structure. Generally, the taller the building, the longer its T_1; the heavier the building, the longer its T_1; and the stiffer the building, the shorter its T_1. For short-period buildings it is expected that most of the seismic response (dynamic energy) along a given direction is transmitted within the first mode of vibration. As a very approximate rule of thumb, the equation $T_1 = 0.1N$ multiplies the number of stories (N) in a building by 0.1s, although ASC restricts this approach to concrete and steel frames. For stiff single-story buildings T_1 is expected to be around 0.05s (Charleson, 2008). Most seismic codes provide empirical formulas to determine the characteristic period T_1 along each main direction of the building. Methods that are based on determination of lateral elastic displacements, requiring a Finite Element model, or following the Rayleigh method, are left out of this analysis as these cannot be performed by simplified hand calculations. For S-ELF in PAK-07 it is not required to calculate T_1, and TAJ-18 does not include any formula.

The most generally used approximate formula $T_1 = C_t \cdot H^{3/4}$ is applicable to all structural systems, provided the building height does not exceed 40m (EC8) or 120ft (ASC). It applies to both principal directions of the building and mainly depends on its height H, which is multiplied by a numerical coefficient C_t based on structural type; around 0.05 for masonry shear walls. The definition of height as measured from the base is different in the codes. IND-16 and EC8 take the top of the structure, whereas AFG-12, ASC and IRN-15 use the average height of the pitched roof. NEP-20, PAK-07 (ELF) and TUR-18 limit the height to the uppermost main portion of the structure (top of walls), which seems most appropriate for the case study buildings where 98% of all mass is in the walls. For URM, Priestly et al (2007) recommend a reduced height of $0.8 \cdot H_n$ for multi-story buildings (H_n= total height as defined in EC8). The influence of height becomes apparent in the calculated values for T_1 in **Table 21A**. It is further noted that NEP-20 makes the period estimation value larger by introducing an extra multiplier of 1.25.

IND-16 determines T_1 for each base dimension along the considered direction of earthquake shaking. Longer and stiffer walls produce shorter periods, and as the full base dimensions are used, this results in lower values of T_1 in the x-direction, **Table 21B**. However, this equation does not consider the openings in the walls, whereas in both case study buildings the percentage of shear walls in the transverse y-direction is dominant. PAK-07 (ELF) and EC8 introduce alternative equations to calculate C_t in relation to the combined effective area of all individual shear walls in the first story of the structure. The calculated values for T_1 show that the x-direction produces the longer period, and therefore seem most realistic for rubble stone masonry buildings, **Table 21C**. TUR-18 introduces a similar equation, but only applicable for concrete shear walls. The alternative method in AFG-12, ASC-10 and (slightly adjusted in) ASC-16 is developed by Goel and Chopra (1998), but for tall buildings with concrete shear walls. For low-rise heavy masonry buildings however, the equations produce too low values and contain errors, **Table 21D**. AFG-12 has incorrectly copied the formula by omitting a factor ^2 and mixing an imperial-based coefficient within their metric-based code. Furthermore, values for T_1 in the metric system are 10x lower than those in feet. These observations were sent to the responsible committee of ASCE whom confirmed that the equations need revision (Charney, 2019).

Table 21. *Comparison of equations and calculations of Natural Periods of Vibration for the case study buildings.*

Code	Equation	Dir.	House			School		
A. Approximate equations 1			k_t, C_t	h (m)	T (s)	k_t, C_t	h (m)	T (s)
NEP-20	$T_1 = (k_t \cdot H^{3/4}) \cdot 1.25$	x,y	0.0500	5.35	0.220	0.0500	2.95	0.141
PAK-07 (ELF)	$T = C_t \cdot (h_n)^{3/4}$	x,y	0.0488	5.35	0.172	0.0488	2.95	0.110
AFG-12, ASC	$T_a = C_t \cdot h_n^{\,x}$ $(^x = 0.75)$	x,y	0.0488	5.88	0.184	0.0488	3.75	0.132
IRN-15	$T = 0.05 \cdot H^{3/4}$	x,y	0.0500	5.88	0.189	0.0500	3.75	0.135
TUR-18	$T_{pA} = C_t \cdot H_N^{\,3/4}$	x,y	0.0700	5.35	0.246	0.0700	2.95	0.158
EC8	$T_1 = C_t \cdot H^{3/4}$	x,y	0.0500	6.77	0.210	0.0500	5.17	0.171
B. Approximate equations 2			D' (m)	h (m)	T (s)	D' (m)	h (m)	T (s)
IND-16	$T_a = (0.09 \cdot H) / \sqrt{D'}$	x	7.75	6.77	0.219	19.40	5.17	0.106
		y	5.50	6.77	0.260	6.70	5.17	0.180
C. Alternatives for Ct (for use in equations of 21A.)			$C_{t,alt}$	h (m)	T (s)	$C_{t,alt}$	h (m)	T (s)
PAK-07 (ELF)	$C_t = 0.0743 / \sqrt{A_c}$	x	0.0528	5.35	0.186	0.0369	2.95	0.083
	$A_c = \sum A_e \cdot (0.2 + (D_e / h_n)^2)$	y	0.0288	5.35	0.101	0.0241	2.95	0.054
EC8	$C_t = 0.075 / \sqrt{A_c}$	x	0.0586	6.77	0.246	0.0490	5.17	0.168
	$A_c = \sum A_i \cdot (0.2 + (l_{wi} / H)^2)$	y	0.0349	6.77	0.146	0.0244	5.17	0.084
D. Alternative equations[1]			C_w	h	T (s)	C_w	h	T (s)
AFG-12 (in m)	$T_a = (0.0019 / \sqrt{C_w}) \cdot h_n$	x	27.2328	5.88	0.002	3.7439	3.75	0.004
	$C_W = \frac{100}{A_B} \cdot \sum_{i=1}^{x} (\frac{h_n}{h_i})^2 \cdot \frac{A_i}{(1 + (0.83 \cdot (\frac{h_i}{D_i}))}$	y	43.8807	5.88	0.002	8.5402	3.75	0.002
ASC-10 (in feet)	$T_a = (0.0019 / \sqrt{C_w}) \cdot h_n$	x	8.0876	19.29	0.013	1.8074	12.30	0.017
	$C_W = \frac{100}{A_B} \cdot \sum_{i=1}^{x} (\frac{h_n}{h_i})^2 \cdot \frac{A_i}{(1 + (0.83 \cdot (\frac{h_i}{D_i})^2)}$	y	28.5799	19.29	0.007	9.2610	12.30	0.008
ASC-16 (in m)	$T_a = (0.00058 / \sqrt{C_w}) \cdot h_n$	x	1.6966	5.88	0.003	1.1182	3.75	0.002
	$C_W = \frac{100}{A_B} \cdot \sum_{i=1}^{x} \frac{A_i}{(1 + (0.83 \cdot (\frac{h_i}{D_i})^2)}$	y	6.2354	5.88	0.001	5.7273	3.75	0.001

$T_a = T_1 = T = T_{pA}$	Approximate natural period of vibration of the first mode of the structure (in s)
$H = h = h_n = H_N$	Height from base to determined level (in m)
D'	Base dimensions of the building at plinth level along the considered direction of shaking (in m)
$k_t = Ct = C_{t,alt}$	Numerical coefficient related to the lateral-resisting system
$A_c = C_w$	Coefficient for combined effective area of the shear walls in the first story of the structure
A_B	Area of the base of the structure (in m^2)
$A_e = A_i$	Effective cross-sectional area of a shear wall in the first story, in the direction considered (in m^2)
h_i	Height of a shear wall (in m)
$D_e = l_{wi} = D_i$	Length of a shear wall in the first story of the structure, in the direction parallel to the applied forces (in m), where (D_e / h_n) and $(l_{wi} / H) < 0.9$
Note: [1]	All formulas for T_a in this section and C_w in AFG-12 contain errors and need revision

5.4.8 Spectral Amplification

The shape of the response spectrum (actually pseudo-acceleration response spectrum but there is no significant difference for low values of damping) shows an idealization of how the natural period of vibration and damping of a building affect its response to earthquake ground motions, in terms of the maximum amplification of $PGA_{surface}$. The shape is illustrated as 4 branches of which only the first two segments are of interest for the case study buildings. The short-period response, starting with the anchor point (PGA) and the linearly increasing spectral acceleration, is followed by the constant spectral acceleration plateau. **Figure 27** shows the first two branches of the elastic (unreduced) response spectra for rock soil with 5% viscous damping, for all selected countries. The conventional damping ratio $\zeta = 5\%$ is generally accepted for all types of masonry, while the structural behavior factor (next section) in the codes is usually calibrated for 5% viscous damping. However, this may need future validation as only limited data is available on viscous damping ratios for stone masonry with lime-based or mud mortars, with high variation in outcomes ranging between 2%-9% (Mazzon et al (2009), Elmenshawi et al (2010)), whereas no data was found for stone masonry with cement mortar.

The corners of the plateau are usually fixed and given by the codes, where the first control point for the linear acceleration is ranging between an average interpolated value of 0.06s (AFG-12) and 0.15s (EC8), whereas the second control point ranges between 0.2s (CN-GB) and 0.5s (NEP-20). This low value in China, resulting in a response spectrum with a very short plateau, may only occur at locations very near to faults (named "design seismic group 1"). The control points for the US-based and Turkish codes are not fixed and must be determined on a case-to-case basis as a relation between the ordinates at long and short periods ($0.2 \cdot S_{D1}/S_{DS}$ and S_{D1}/S_{DS}) and depending on soil type. **Figure 27** shows the averages of 25 randomly calculated values as taken from the Afghan (ABC-12) and Turkish (Decree BKK-2018/11275, 2018) hazard maps. NEP-20 and IND-16 have normalized the full spectral acceleration to the maximum plateau value. Iran includes two response spectra, one for low-to-moderate, and the other for high-to-very high seismic levels (which is shown here in this section).

The calculated values for T_1 are added to **Figure 27**, showing that for both directions of the buildings, almost all ordinates fall within the constant plateau. This means that the spectral amplification is maximum (and most conservative) with a value of 2.5 for all countries except China, where the spectral amplification is maximized at 1/0.45=2.222 (generally rounded to 2.25). No spectrum is included for S-ELF (PAK-07), other than the introduction of a more conservative shape factor ($C_a \cdot 3.0$ in the numerator). AFG-12 makes S-ELF more conservative by introducing an extra multiplier (F) related to the number of floors above grade. TAJ-18 also includes a coefficient related to the building height, $K_3 = 1.0$ for ≤ 5 stories. As China defines the same height as AFG-12 (halfway pitched roof), the same values for T_1 are assumed on the Chinese spectrum (CN-GB). In Iran the amplification is called "building behavior factor B", determined as $B=S+1=2.5$ since the soil parameter S is always 1.5 on the plateau for rock soil. Although T_1 is not calculated for Tajikistan, it is assumed it falls on the plateau with maximum amplification $\beta_1 = 2.5$. Only once T_1 falls outside the plateau, for the y-direction of the school in EC8 (**Table 21C**), resulting in a reduced amplification. As a point of attention, Kwon & Kim (2010) note that the approximate formulas (**Table 21A**) overestimate the natural period. For low-rise masonry buildings this may lead to more conservative seismic design, as values that are approximated on the constant plateau may realistically fall within the first linear branch of the response spectrum. They further note that C_t for shear walls has not been recalibrated since the 1990s and propose a value reduced by 25%. However, a quick check of the empirical calculations with such adjusted value ($C_t = 0.375$) shows no difference in the outcomes.

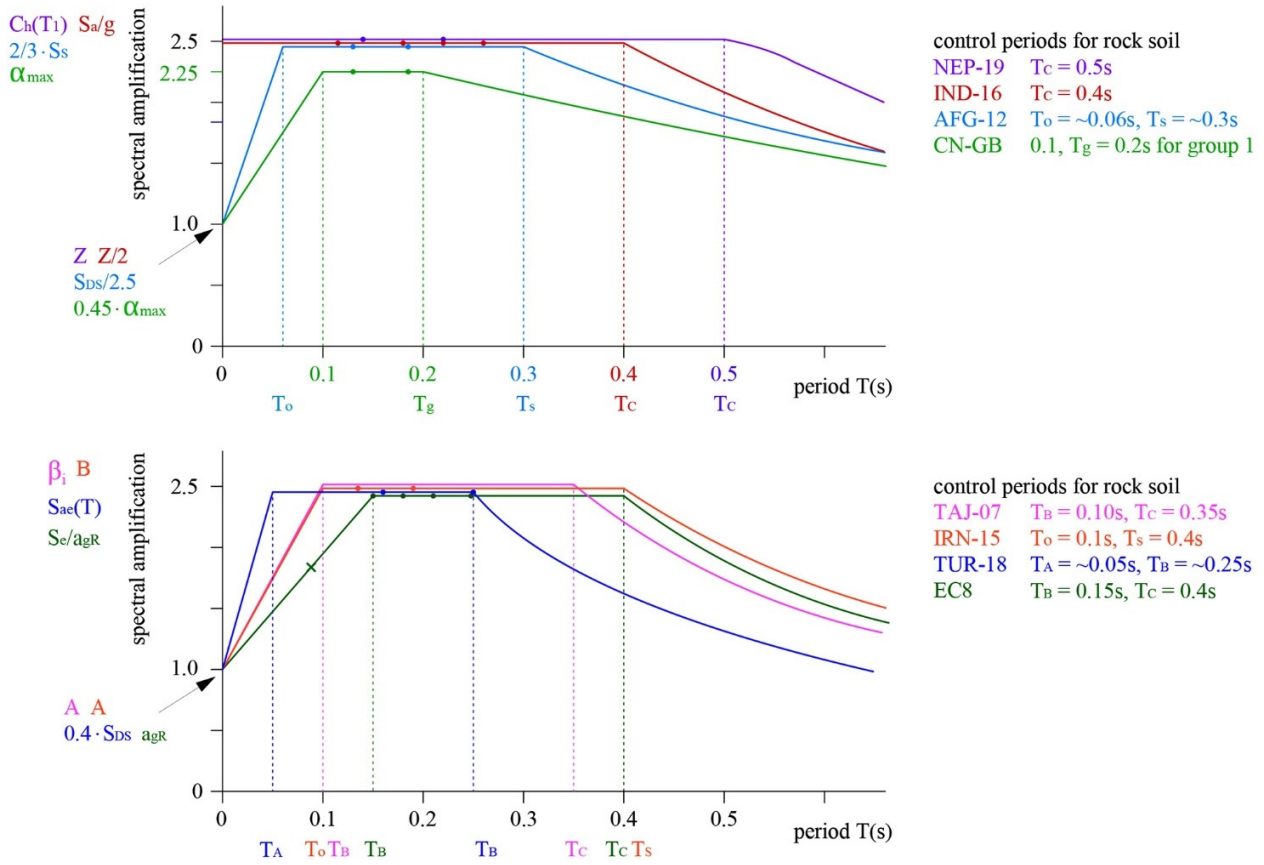


Figure 27. *Linear increasing spectral acceleration and constant spectral acceleration plateau of elastic response spectra for rock soil with 5% viscous damping, according to the seismic codes of (A) Nepal, India, Afghanistan, China, and (B) Tajikistan, Iran, Turkey, Croatia.*

5.4.9 Structural Behavior Factor

The structural behavior factor allows for a reduction of the elastic spectral acceleration, by introducing non-linear (inelastic) mechanisms inherent to the structural typology and materials of the building, such as yielding, ductility, overstrength and energy dissipation properties. Therefore, codes make a clear distinction between the elastic unreduced response (requiring no damage, generally for SLS) and the reduced design spectrum (allowing acceptable damage but no collapse, usually adopted for ULS). Generally, the inelastic range for stone masonry is expected to be very limited due to the relative brittleness of the mortar. However, good quality stone masonry possesses substantial displacement and energy dissipation capacity, as well as exhibits large non-linear deformation capacity with moderate damage levels (Tomazevic and Lutman (2007), Vasconcelos and Lourenço (2009)). This can be further enhanced by an interlocking masonry pattern with strong mortar, and by inclusion of continuous horizontal bands for improved box behavior. Although limited test data is available for these effects on stone masonry, a behavior factor around 1.8-2.0 seems achievable (Benedetti et al (1998), Ali et al (2013)), which is in line with the recommendations in most codes. As with many segments in this chapter, also this important parameter needs further validation as it highly influences the total base shear.

Several codes have included a specific behavior factor for the typology of nominally reinforced shear wall masonry with horizontal bands, usually taken as R = 2.0 (IND-16, AFG-12). NEP-20 specifies a ductility factor R_μ = 2.0 for NRM with both bands and vertical steel rods, to be multiplied by an overstrength factor Ω_u = 1.2. Without vertical rods it is assumed that $R_\mu \cdot \Omega_u$ = 2.0, similar to India, although in their latest National Building code, India introduces a minimum requirement of reinforcements in URM that equals R = 2.5 and restricts its use to seismic zones II and III only. However, this national code itself indicates that "it is non-statutory in nature" (IS:SP7-2016, 2016) and therefore R = 2.0 is generally applied. EC8 recommends values between 1.5-2.5 and restricts this up to $a_{g,urm}$ = 0.2g, which is set at q= 2.0 for all seismic hazards by Croatia, currently the only European country that allows rubble stone masonry in their National Annex (nHRN EN 1998-1:2011/NA, 2011). Iran provides no R-factor since verifications are not needed for NRM, therefore R = 2.0 is assumed. Deviations from the general approach of R = 2.0 are also observed. For reasons that are not further explained, PAK-07 (following UBC-97) uses a very high factor R = 4.5 for masonry bearing walls. China does not include a separate behavior factor, as they dictate SLS-verification as their primary objective level, which is related to fully elastic behavior. For ULS-verifications China introduces a different set of seismic coefficients with higher accelerations values (2.8 times higher). TAJ-18 reduces the spectrum with coefficients that considers the structural typology (K_2 = 1.45 for masonry) and energy dissipation (K_ψ = 1.0), amounting to a total reduction of $1/(K_2 \cdot K_\psi)$ = 0.69. Turkey mostly deviates, as their seismic load reduction coefficient $R_a(T)$ includes a variable T/T_B, resulting in a linear increasing amplification toward the second control point T_B, as opposed to a constant plateau in all other codes. For this reason, the bottom of the denominator cannot be rewritten into the conceptual formula; base shear must be calculated on a case-to-case basis for each ordinate on the seismic hazard map. All Behavior Factors are added to **Table 22**.

5.4.10 Importance Factor

A last modification of the lateral loads is introduced by the importance of the building, representing different risk levels based on function and occupancy. All codes assign a factor 1.0 to ordinary (residential) buildings, and a higher factor between 1.2 - 1.5 to schools, as these pose a larger risk due to higher occupancy. They should also remain operational after a disaster, for instance after the 2015 Gorkha Earthquake, the schools of SSF acted as first-aid posts and temporary shelter for villagers that lost their house, or were afraid to return home. PAK-07 however makes a distinction between primary-and-secondary schools (group E-1 with 50-300 students) and higher educational buildings (group A), therefore both the house and three-classroom school are assigned to occupancy category 4 with I = 1.0. It is further noted that S-ELF (PAK-07, AFG-12) has no importance factor in its formula. China (GB 50223-2008, 2008) approaches the importance differently, by assigning importance categories to buildings (house = B, school = C). First the design coefficient is determined based on performance objectives (earthquake level) and site conditions (fortification intensity level). The same coefficient is used for both buildings, but the design requirements for the school must meet those of one intensity level higher, which are stricter in terms of height and overall dimensions. TAJ-18 deviates largely with importance factor K_1 = 0.25 for houses and a 40% increase to K_1 = 0.35 for schools. TUR-18 defines building classes based on importance (house = BSK-3, school = BSK-1), which then are further related to maximum allowed height classes (BYS) and types of analysis. For URM, houses can only be built in BYS-8 (H_N < 10.5m and S_{DS} < 0.50) and schools are not allowed for "structural systems with limited ductility". EC8 has coupled the importance factor γ_I directly to the reference PGA for soil type A ($a_g = \gamma_I \cdot a_{gR}$) and recommends γ_I = 1.2 for schools. All Importance Factors are added to **Table 22**.

5.4.11 Comparison of Base Shear

To compare the base shear as calculated by the ELF method (or similar), all necessary code-specified values are added to **Table 22**, while expressing the formulas as follows: "Base Shear = PGA· C_{RS} · W". The coefficient C_{RS} represents an "amplification factor specifically for low-ductile rubble stone masonry buildings", as a product of the maximum amplification of PGA, divided by the structural behavior of the building. By extracting the design PGA and assuming that the seismic weight is constant, the implications for the base shear according to each national code can be easily compared for any given seismic hazard. The table separates between houses (**Table 22A**) and schools (**Table 22B**) by means of the importance factor, resulting in coefficients $C_{RS,H}$ and $C_{RS,S}$.

Table 22. *Comparison of conceptual base shear formulas on rock soil for rubble stone masonry buildings.*

A. House	**Spectral acceleration**				**Reduction**		**Imp.**	[1]C_{RS}	Notes
Country	PGA	Soil	Amplification		Behavior factor		I_H	[1]$C_{RS,H}$	
NEP-20	Z	A-C	$C_h(T)$	2.5	$R_\mu \cdot \Omega_u$	2.0	1.0	1.25	R for horizontal bands only
IND-16	$Z/2$	all	S_a/g	2.5	R	2.0	1.0	1.25	
PAK-07! S-ELF	C_a	S_B		3.0	R	4.5	-	0.67	$S_B = 1.0$
AFG-12! ELF	$(2/3 \cdot S_s) / 2.5$	F_a		2.5	R	2.0	1.0	1.25	$F_a = 1.0$
AFG-12! S-ELF	$(2/3 \cdot S_s) / 2.5$	F_a	F	2.75	R	2.0	-	1.38	$F_a = 1.0$, $R = 2.0$, $F = 1.1$
CN-JGJ	$0.45 \cdot \alpha_{maxb}$	all	~1/0.45	2.25	-	-	-	2.25	
TAJ-18 S-mod.	A	$I_{(soil)}$	$\beta_i \cdot K_3$	2.5	$1/(K_2 \cdot K_\psi)$	0.69	0.25	$0.91 \cdot$ [3]η_{tot}	β_i=2.5, K_3=1.0, K_2=1.45, K_ψ=1.0
IRN-15	A	$I_{(soil)}$	B	2.5	R_u	2.0	1.0	1.25	
CRO-11	a_{gR}	S		2.5	q	2.0	1.0	1.25	$S = 1.0$
B. School	**Spectral acceleration**				**Reduction**		**Imp.**	[1]C_{RS}	Notes
Country	PGA	Soil	Amplification		Behavior factor		I_S	[1]$C_{RS,S}$	
NEP-20	Z	A-C	$C_h(T)$	2.5	$R_\mu \cdot \Omega_u$	2.0	1.5	1.88	R for horizontal bands only
IND-16	$Z/2$	all	S_a/g	2.5	R	2.0	1.5	1.88	
PAK-07! S-ELF	C_a	S_B		3.0	R	4.5	-	0.67	
AFG-12! ELF	$(2/3 \cdot S_s) / 2.5$	F_a		2.5	R	2.0	1.25	1.56	
AFG-12! S-ELF	$(2/3 \cdot S_s) / 2.5$	F_a	F	2.5	R	2.0	-	1.25	$F = 1.0$ (1 story)
CN-JGJ	$0.45 \cdot \alpha_{maxb}$	all	~1/0.45	2.25	-	-	-	2.25	
TAJ-18 S-mod.	A	$I_{(soil)}$	$\beta_i \cdot K_3$	2.5	$1/(K_2 \cdot K_\psi)$	0.69	0.35	$1.27 \cdot$ [3]η_{tot}	
IRN-15	A	$I_{(soil)}$	B	2.5	R_u	2.0	1.2	1.50	
CRO-11	a_{gR}	S	x-dir	2.5	q	2.0	1.2	1.50	
			y-dir	[2]0.99		-	1.2	1.19	$T_1 = 0.084$s, $T_B = 0.15$s, $R = 2.0$

Note: for definition of symbols see Table 19
! = Rubble stone masonry not allowed
[1] C_{RS} = Amplification factor for rubble stone masonry buildings; includes all coeff. except PGA and seismic weight
[2] Amplification for reduced design spectrum in first branch = $2/3 + (T/T_B).((2.5/q)-2/3)$
[3] η_{tot} = Sum of level distribution factors for mode i=1 and levels k. For the case studies: $\eta_{tot,house} = 0.90$ and $\eta_{tot,school} = 1.0$

For houses, it shows that the base shears in NEP-20, IND-16, AFG-12 (ELF), IRN-15 and CRO-11 are equal, and comparable for AFG-12 (S-ELF). Pakistan is roughly two times more tolerant compared to its neighboring countries, mainly caused by the high value of the behavior factor R = 4.5. In their highest seismic zone 4 (only), C_{RS} must be multiplied with a near-fault factor N_a = 1.1. In Tajikistan, C_{RS} is also significantly lower and for the house must be further reduced by 10%, due to the partial

inclusion of seismic weight ($\eta_{tot,house}$ = 0,90). CN-JGJ on the other hand is nearly two times more conservative than its neighbors, although the design seismic coefficient α_{maxb} = 0.9 for the highest seismic zone (0.40g at precautionary level), seldom needs to be applied (**Figure 25B**). For schools, variation between the codes is wider due to the different values for Importance factor *I*. Usually, $C_{RS,S}$ is higher than $C_{RS,H}$ (NEP-20, IND-16, TAJ-18, IRN-15). PAK-07 and CN-JGJ however make no difference between houses and schools (for < 300 students in Pakistan). In AFG-12 the difference between ELF and S-ELF is 10% higher for the house due to factor F_H = 1.1 (2 stories) versus F_S = 1.0 for the school (1 story). This results in lower base shear for schools in Afghanistan, which is contrary to all other codes where buildings of higher importance demand a higher design force. In CRO-11 the base shear is reduced for the y-direction of the school, as T_1 falls on the first branch of the response spectrum (**Figure 27**), for which a different formula applies.

Further, the differences are analyzed when multiplying C_{RS} with PGA values of directly bordering areas, as mapped in **Figures 25A,B** and **26A,B**. In the Western Himalayas, the highest Indian value 0.18g connects with 0.20g in China (Tibet) and 0.40 in Nepal and Pakistan. Still, base shear between India and Pakistan is comparable, while it doubles in China and Nepal (**Table 23A**). Differences around the Tian Shan mountains are much larger, as base shear is nearly 6x higher in China compared to Tajikistan (**Table 23B**), whereas the values bordering Armenia (except with Georgia) are more similar despite the high variation of design accelerations (**Table 23C**). For Turkey calculations can only be made on a case-to-case basis, thus an average value S_s for 25 regional coordinates was determined. All comparisons together give a good indication that in terms of base shear alone, Pakistan and Tajikistan are most tolerant, and China is most conservative toward rubble stone masonry. However, to complete the analyses, the distribution of forces and load combinations must also be considered.

Table 23. *Comparison of conceptual base shear for actual PGA values in bordering regions.*

A. Comparison of base shear coefficients for PGA values at bordering areas in Western Himalayas; for house design			
Country	**Base shear formula**	**Values for case study house**	**Base shear** = [1]$C_{RStot} \cdot W$
NEP-20	$(Z \cdot C_h(T_1))/(R_\mu \cdot \Omega_u) \cdot I$	$Z = 0.40$, $C_h(T_1) = 2.5$, $R_\mu \cdot \Omega_u = 2.0$, $I = 1.0$	$V = 0.50 \cdot W_t$
IND-16[!!]	$((Z/2) \cdot (S_a/g)/R) \cdot I$	$Z/2 = 0.18$, $S_a/g = 2.5$, $R = 2.0$, $I = 1.0$	$V_B = 0.23 \cdot W$
PAK-07[!] S-ELF	$((C_a \cdot N_a) \cdot 3.0)/R$	$C_a = 0.40$, $N_a = 1.1$, $R = 4.5$	$V = 0.29 \cdot W$
CN-JGJ[!!]	α_{maxb}	$\alpha_{maxb} = 0.45$ (for 0.20g at precautionary level)	$F_{Ekb} = 0.45 \cdot G_{eq}$
B. Comparison of base shear coefficients for PGA values at bordering areas of Tian Shan mountains; for house design			
TAJ-18	$((A \cdot \beta_i \cdot K_3)/R) \cdot K_1 \cdot \Sigma\eta_k$	$A = 0.20$, $\beta_i \cdot K_3 = 2.5$, $R = 0.69$, $K_1 = 0.25$, $\Sigma\eta_k = 0.90$[2]	$S_k = 0.16 \cdot Q_k$
KYR-18[!]	$(A_{gR} \cdot S_T \cdot 2.5/q) . \gamma_{Ih} \cdot \Sigma\eta_k$	$A_{gR} = 0.50$, $S_T = 1.0$, $q = 2.0$, $\gamma_{Ih} = 1.0$, $\Sigma\eta_{ik} = 0.90$[2]	$F_{ik} = 0.56 \cdot w_k$
CN-JGJ[!!]	α_{maxb}	$\alpha_{maxb} = 0.90$ (for 0.40g at precautionary level)	$F_{Ekb} = 0.90 \cdot G_{eq}$
C. Comparison of base shear coefficients for PGA values at bordering areas with Armenia; for house design			
GEO-09[4]	$((A \cdot K_0 \cdot \beta_i)/R) \cdot K_3 \cdot \Sigma\eta_k$	A=0.15, K_0=1.2, β_i=2.5, R=1.92, K_3=1.0, $\Sigma\eta_k$=0.90[2]	$S_{ik} = 0.21 \cdot Q_k$
ARM-20[!]	$((A \cdot K_0 \cdot \beta_i)/R) \cdot K_2 \cdot \Sigma\eta_k$	A=0.40, K_0=0.8, β_i=2.5, R=1.67, K_2=1.0, $\Sigma\eta_k$=0.90[2]	$S_{ki} = 0.43 \cdot Q_k$
AZE-14[!]	$((a_o \cdot K_q \cdot \beta_i)/R) \cdot K_1 \cdot \Sigma\eta_k$	a_o=0.50, K_q=0.7, β_i=2.5, R=2.22, K_1=1.0, $\Sigma\eta_k$=0.90[2]	$S_{ik} = 0.35 \cdot Q_k$
IRN-15	$((A \cdot B)/R_u) \cdot I$	$A = 0.30$, $B = 2.5$, $R_u = 2.0$, $I = 1.0$	$V_u = 0.38 \cdot W$
TUR-18[!]	$S_S \cdot F_S/((D+(R/I)-D) \cdot (T/T_B))$	$S_{S,av}$=0.781, F_S=0.9, D=1.5, R=2.5, I=1.0, T=T_B=0.26	$S_{tE} = 0.28 \cdot W_t$

Note: for definition of symbols see Table 19; symbols for Georgia, Kyrgyzstan, Armenia and Azerbaijan not included
[!] = Rubble stone masonry not allowed
[!!] = Rubble stone masonry allowed under certain conditions, but not for this particular PGA
[1] C_{RStot} = Amplification factor for rubble stone masonry buildings; includes all coeff. and PGA, except seismic weight
[2] η_{tot} = Sum of level distribution factors for mode i=1 and levels k. For the house: $\eta_{tot,house}$ = 0.90
[3] Kyrgyzstan does not allow the simplified modal method for first mode only
[4] Georgia is in the process of adopting Eurocode 8

5.5 Calculation Examples of Base Shear and Distribution of Loads

To finalize the seismic demand of the case study buildings, this section calculates and analyzes the base shears, distribution of lateral forces over the floors, and redistribution of the loads over the individual masonry panels. A medium earthquake level of PGA = 0.2g is chosen, which is allowed in Iran and Croatia, and in line with the upper limit for rubble stone buildings in Tajikistan and India (0.18g, although rubble stone is not allowed). This is however higher than permitted in China (≤ 0.15g), but lower than in Nepal where PGA values start at 0.25g.

5.5.1 Base Shear and Distribution of Story Shears

The first step is to calculate the base shear for 0.2g (or S_{DS} = 0.50) with the formulas for each country of **Table 19**, the coefficients C_{RS} of **Table 22**, and the seismic weights of **Table 17**. This results in the base shears presented in **Table 26**, confirming that Pakistan is most tolerant and China most conservative regarding the total base shear. For the house, the average of all 9 countries closely matches V_{base} in Nepal, which therefore is taken as the reference country, whereas the percentual difference between the other countries is shown in the third column. The base shears are vertically distributed over the top level (F_2) and first floor level (F_1) of the house, with the distribution formulas of **Table 24**. In Tajikistan this sequence is reversed; first the horizontal lateral loads are calculated for each floor level separately with consideration of the level distribution factor η_{ik}, which then amount to the total base shear. The values of F_2 and F_1 are also added to **Table 26**, showing an almost even division for all countries due to a triangular distribution of the story shears. The only exception is India, which introduces a parabolic distribution for all buildings regardless of their height. Some countries have included an extra force at the top in their formula, which for low-rise buildings can be ignored.

Table 24. *Formulas for vertical distribution of story shear.*

Country	Vertical Distribution	Country	Vertical Distribution
IND-16	$Q_i = \frac{W_i \cdot h_i^2}{\sum_{j=1}^{n} W_j \cdot h_j^2} \cdot V_B$	PAK-07, TUR-18	$F_x = \frac{w_x \cdot h_x}{\sum_{i=1}^{n} w_i \cdot h_i} \cdot (V - F_t)$ where $F_t = 0$
TAJ-18	$\eta_{ik} = \frac{x_k \cdot \sum_{j=1}^{n} Q_j \cdot x_j}{\sum_{j=1}^{n} Q_j \cdot x_j^2}$	All others	$F_i = \frac{W_i \cdot h_i}{\sum_{i}^{n} W_i \cdot h_i} \cdot V$
$Q_i = F_x = F_i$	= Design story shear or lateral seismic force induced at floor level *i* or *x*		
η_{ik}	= Level distribution factor for mode *i* at level *k*		
F_i	= Concentrated force at the top		
$W_i = Q_j = w_x$	= Seismic weight of the building assigned to level *i* or *j*		
$h_i = h_x = x_k = x_j$	= Heights at level *i, j, k* or *x*		
$V_B = V$	= Total design seismic base shear		

5.5.2 Load Combinations and Vertical Seismic Loads

All codes include sets of load combinations that combine static with earthquake loads, resulting in an upper and lower limit that must be verified for each seismic-load-resisting element of the buildings. NEP-20 and EC8 include just one combination that is the same for both determination of seismic weights and base shear, as well as for verification of the masonry panels, whereas India introduces

three different sets. All starting combinations are shown in **Table 25**. Then the vertical seismic loads are determined, which is not deemed necessary for low-rise or "simple" buildings in Nepal, China, Iran, Turkey and Eurocode. India introduces a vertical seismic coefficient A_v as two-thirds of the horizontal coefficient A_h, of which 30% is added to the load combination, and which affects both *DL* and *LL*. Similarly, in Tajikistan 15% (zone 8, simplified approach) of vertical loads is combined with the axial force *N*, as acting on the walls only. PAK-07 and AFG-12 relate a fraction of the vertical action only to the portion of *DL*. Since the vertical component acts in both upward and downward directions, and assuming that the effects of the earthquake loads are governing for ULS-verifications, this results in the critical load combinations as shown in **Table 26**. For ease of comparing, the various symbols for Dead, Live and Earthquake loads are made equal (D, L and E), and only the upper and lower limits are included.

Table 25. *Load combinations and vertical seismic loads.*

country	load combinations	vertical seismic load	notes
NEP-20	$1.0 \cdot DL + \lambda \cdot LL \pm 1.0 \cdot E$	-	$\lambda = 0.3$
IND-16	(set 1) $1.2 \cdot [DL + IL \pm EL_{x,y} \pm EL_z]$ (set 2) $1.5 \cdot [DL \pm EL_{x,y} \pm EL_z]$ (set 3) $0.9 \cdot DL \pm 1.5 \cdot (EL_{x,y} \pm EL_z)$	$EL_z = 0.9 \cdot (0.3 \cdot A_v)$ for IL[1] $EL_z = (0.3 \cdot A_v)$ for DL	only in zones IV&V; $A_v = 2/3 \cdot A_h$ $(0.3 \cdot A_{v,house}) = 0.05$ for 0.2g $(0.3 \cdot A_{v,school}) = 0.075$ for 0.2g
PAK-07	$1.2 \cdot D + f_1 \cdot L + 1.1 \cdot E$ $0.9 \cdot D \pm 1.1 \cdot E$	$E = \rho \cdot E_h + E_v$ $E_v = 1.1 \cdot (0.5 \cdot C_a \cdot I \cdot D)$	$f_1 = 0.5$ $\rho = 1.0$ and $E_v = 0.11 \cdot D$ for 0.2g
AFG-12	$(1.2 + 0.2 \cdot S_{DS}) \cdot D + 0.5 \cdot L + \rho \cdot Q_E$ $(0.9 - 0.2 \cdot S_{DS}) \cdot D + \rho \cdot Q_E$	$E = \rho \cdot Q_E \pm E_v$ $E_v = 0.2 \cdot S_{DS} \cdot D$	for $S_{DS} > 0.125$ (PGA > 0.05g) $\rho = 1.0$, $E_v = 0.1 \cdot D$ for $S_{DS} = 0.50$
CN-JGJ	$1.0 \cdot G_{eq} + 1.0 \cdot E$	-	$G_{eq} = 1.0 \cdot DL + 0.5 \cdot LL$ for 1-story $G_{eq} = 0.95 \cdot DL + 0.95 \cdot (0.5 \cdot LL)$ for 2-story
TAJ-18	$1.0 \cdot DL + 1.0 \cdot LL \pm 0.5 \cdot E_v \pm 1.0 \cdot E_h$ $1.0 \cdot DL + 1.0 \cdot LL \pm 1.0 \cdot E_v \pm 0.5 \cdot E_h$	$E_v = N_v = 0.15 \cdot N$	for zone 8
IRN-15	$1.2 \cdot D + 1.0 \cdot L + 1.0 \cdot E$ $0.9 \cdot D + 1.0 \cdot E$	-	
TUR-18	$1.0 \cdot G + 1.0 \cdot Q + 1.0 \cdot E_d^{(H)}$ $0.9 \cdot G + 1.0 \cdot E_d^{(H)}$	-	
EC8	$1.0 \cdot G + \psi_2 \cdot Q + 1.0 \cdot E_d$	-	$\psi_2 = 0.3$

$\lambda = f_1 = \psi_2$	= Combination coefficient
$DL = D = G$	= Dead Load
$LL = IL = L = Q$	= Live Load
G_{eq}	= Gravity Load; sum of portions of DL and LL
$E = EL_{x,y} = EL_z = Q_E = E_h = E_v = E_d^{(H)} = E_d$	= Earthquake Load (in x- or y-direction)
$EL_z = E_v$	= Earthquake Load (in z-direction)
A_v	= Vertical seismic coefficient
ρ	= Redundancy factor

[1] *IL* is 10% reduced for 2-story buildings according to IS.875(pt.2)-2007

Table 26. *Final calculations of base shear, story shears, and forces acting on selected masonry panels for the house and the school in random rubble sandstone masonry.*

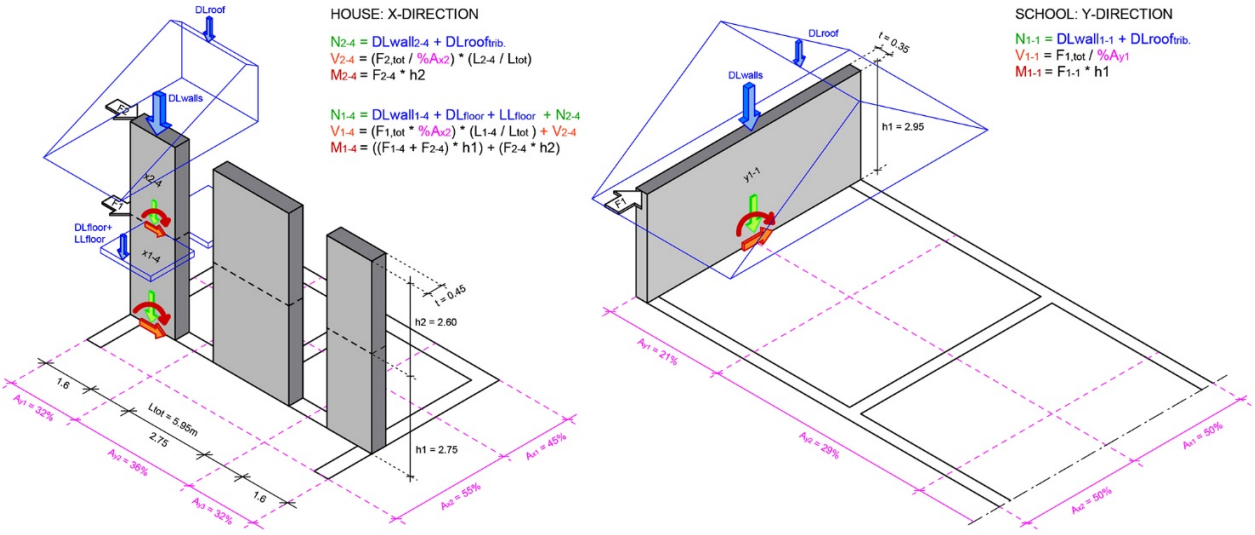
A. House in sandstone masonry calculated for 0.2g, with Forces (kN) and Moments (kNm) acting on panel X1-4									
Country	V_{base}	**%**	F_2	F_1	**Critical Load Combinations**	***N***	***V***	***M***	**%**
NEP-20	276.0	**ref.**	136.1	140.0	$1.0 \cdot D + 0.3 \cdot L \pm 1.0 \cdot E$	97.1	41.0	165.2	**ref.**
							[1](67.9)	[1](273.4)	**-**
IND-16[!]	275.1	-0.3	180.3	94.9	$1.58 \cdot D \pm 1.5 \cdot E$ [3]	148.7	61.3	272.9	+65.2
					$0.83 \cdot D \pm 1.5 \cdot E$ [4]	78.1			
PAK-07[!]	141.5	-48.7	70.8	70.7	$1.31 \cdot D + 0.5 \cdot L \pm 1.1 \cdot E$	125.0	23.1	93.6	-43.3
					$0.79 \cdot D \pm 1.1 \cdot E$	72.3			
AFG-12[!]	291.9	+5.8	146.0	145.9	$1.3 \cdot D + 0.5 \cdot L \pm 1.1 \cdot E$	124.1	43.3	175.5	+6.2
					$0.8 \cdot D \pm 1.1 \cdot E$	73.3			
CN-JGJ	457.9	+65.9	225.2	232.7	$0.95 \cdot D + 0.475 \cdot L \pm 1.0 \cdot E$	89.9	68.0	273.8	+65.7
TAJ-18	189.9	-31.2	90.9	99.0	$1.075 \cdot D + 1.075 \cdot L \pm 1.0 \cdot E$	131.8	28.2	112.6	-31.8
					$0.925 \cdot D + 0.925 L \pm 1.0 \cdot E$	113.4			
					$1.15 \cdot D + 1.15 \cdot L \pm 0.5 \cdot E$	141.0	14.1	56.3	-65.9
					$0.85 \cdot D + 0.85 \cdot L \pm 0.5 \cdot E$	104.2			
IRN-15	280.6	+1.7	138.8	141.8	$1.2 \cdot D + 1.0 \cdot L \pm 1.0 \cdot E$	124.7	41.7	168.1	+1.8
					$0.9 \cdot D \pm 1.0 \cdot E$	86.0			
TUR-18[!]	[5]269.6	-2.3	133.6	136.0	$1.0 \cdot D + 1.0 \cdot L \pm 1.0 \cdot E$	122.0	40.0	161.6	-2.2
					$0.9 \cdot D \pm 1.0 \cdot E$	100.8			
EC8	280.9	+1.8	138.9	142.0	$1.0 \cdot D + 0.3 \cdot L \pm 1.0 \cdot E$	98.3	41.7	168.3	+1.9

B. School in sandstone masonry calculated for 0.2g, with Forces (kN) and Moments (kNm) acting on panel Y1-1								
Country	V_{base}	**%**	$F_1 = V_{base}$	**Critical Load Combinations**	***N***	***V***	***M***	**%**
NEP-20	271.9	**ref.**	271.9	$1.0 \cdot D \pm 1.0 \cdot E$	172.4	56.6	166.8	**ref.**
						[2](84.8)	[2](250.3)	**-**
IND-16[!!]	271.9	0.0	271.9	$1.61 \cdot D \pm 1.5 \cdot E$ [3]	277.6	84.8	250.3	+50.1
				$0.79 \cdot D \pm 1.5 \cdot E$ [4]	136.2			
PAK-07[!]	94.6	-65.2	94.6	$1.31 \cdot D \pm 1.1 \cdot E$	220.1	21.6	63.9	-61.7
				$0.79 \cdot D \pm 1.1 \cdot E$	132.7			
AFG-12[!]	221.7	-18.5	221.7	$1.3 \cdot D \pm 1.1 \cdot E$	218.4	46.1	136.0	-18.5
				$0.8 \cdot D \pm 1.1 \cdot E$	134.4			
CN-JGJ[!!]	315.6	+16.1	315.6	$1.0 \cdot D \pm 1.0 \cdot E$	164.5	65.6	193.7	+16.1
TAJ-18	230.2	-15.3	230.2	$1.075 \cdot D \pm 1.0 \cdot E$	188.6	47.9	141.3	-15.3
				$0.925 \cdot D \pm 1.0 \cdot E$	162.3			
				$1.15 \cdot D \pm 0.5 \cdot E$	201.8	23.9	70.6	-57.7
				$0.85 \cdot D \pm 0.5 \cdot E$	149.1			
IRN-15	221.6	-18.5	221.6	$1.2 \cdot D \pm 1.0 \cdot E$	210.5	46.1	136.0	-18.5
				$0.9 \cdot D \pm 1.0 \cdot E$	157.9			
TUR-18[!]	[5]281.6	+3.6	281.6	$1.0 \cdot D \pm 1.0 \cdot E$	206.4	58.6	172.8	+3.6
				$0.9 \cdot D \pm 1.0 \cdot E$	185.7			
EC8	(x) 221.2	-18.7	(x) 221.2	-	-	-	-	
	(y) 178.2	-34.5	(y) 178.2	$1.0 \cdot D \pm 1.0 \cdot E$	174.4	37.1	109.3	-34.5

ref. = Reference values of Nepal, for use of comparing and scaling to other countries
D = Dead Load, L = Live Load, E = Horizontal Earthquake Load
N = Axial Force, V = Shear Force, M = Bending Moment
! = Rubble stone masonry not allowed
!! = Rubble stone masonry allowed under certain conditions, but not for this particular PGA
[1] For 0.33g for the house in Nepal (comparable to 0.2g in India and China)
[2] For 0.30g for the school in Nepal (comparable to 0.2g in India)
[3] Upper limit of set 2 and [4] lower limit of set 3
[5] For the high-density scenario with granite stone masonry

5.5.3 Axial Forces, Shear Forces and Bending Moments

For the house one slender panel (X_{1-4}), and for the school one stocky masonry panel (Y_{1-1}) are selected to analyze the effects of the critical load combinations on the Axial Forces (*N*), Shear Forces (*V*) and Bending Moments (*M*). A worst-case scenario is assumed where spandrels and sills are fully ignored, as well as the beneficial effects of horizontal bands are neglected. It basically results in the analysis of an URM free-standing cantilevered pier (**Figure 28**), which is not a very realistic scenario, but gives sufficient insight into the seismic demands as dictated by the codes. Since all mass is in the walls, instead of distributing the inertia story forces F_1 and F_2 by tributary areas (for flexible diaphragms), the forces are redistributed by tributary masses according to the lengths of the main walls in the direction under consideration, plus tributary lengths of the orthogonal walls. Due to the slight asymmetry in the house, this results in a division of 45-55% for the walls in x-direction, and 32-36-32% in y-direction. For the school this is 50-50% and 21-29-29-21% respectively.



(A) **(B)**

Figure 28. *Division of mass and internal actions on a cantilevered pier for* ***(A)*** *the house and* ***(B)*** *the school design (all by courtesy of Smart Shelter Foundation).*

The calculated values for *N*, *V* and *M* for the critical load combinations are added to **Table 26**, where for Turkey the highest-density scenario of granite is included. It shows that in almost all cases (except Tajikistan), the load combinations only influence *N*, where the upper limit checks the capacity of the panels in compression, and the lower limit relates to shear along the horizontal joints of the masonry. It is expected that a higher value of *N* is beneficial for stocky panels, whereas lower values of *N* may benefit the bending moment on slender panels. However, identification of the most critical panels can only be determined at a later stage, during a full seismic capacity verification. Overall, **Table 26** shows that base shear (second column) is a good indication of which code is most tolerant (Pakistan) and most conservative (China), as the percentages compared to reference country Nepal, after application of the load combinations (last column), remain in the same range. Only India deviates significantly due to the introduction of a seismic load factor 1.5, making the seismic demand similar to China for the house, and highest of all for the school. These highest values match with PGA = 0.33g for the house and PGA = 0.30g for the school in Nepal. Since Nepal does allow such higher PGA values for rubble stone

(contrary to India and China), these will be taken as the reference and target for the seismic capacity checks in future work. Coincidentally, these reference values closely match the intensity of the 2015 Gorkha Earthquake, with a USGS preliminary estimation of PGA = 0.35g in the epicentral area (Aydan and Ulusay, 2015), and an estimated value of PGA = 0.30g at 60km from the epicenter where the maximum slip was observed (Dhanya et al, 2017). By applying and scaling the percentages in the last column with respect to the Nepali values, the seismic demand implications for different seismic hazards can be determined for each country accordingly. Lastly, the weight implications of different types of stones must be considered, which in Nepal and India amounts to 7.1% and in China to 19.2% additional seismic weight for the uppermost limit of granite stone masonry buildings (not added to the table).

5.6 Conclusion

The total base shear, distribution of forces and load combinations for ULS-verifications (10%PE_{50y}) are analyzed and compared by means of literally applying the seismic codes of selected countries that still (or should) allow the technique of nominally reinforced rubble stone masonry (NRM), for a typical house and school design as built in Nepal. The following is concluded:

- The case study buildings, characterized by heavy stiff walls and light flexible diaphragms, behave differently from most common structures. Main difference is that all lateral-force-generating mass is located in the heavy walls with a ratio of nearly 97.5% versus 2.5% for the diaphragms including *LL* (**Table 16** and **Table 17**). As a result, the floor inertia forces are distributed to the lateral-resisting elements by tributary wall masses.

- Since generation of inertia forces is proportional to mass, it is important to determine the correct stone typology, as large differences exist between densities for sandstone and granite.

- The codes define conventional ways of lumping the seismic weights at floor levels and leave out the lower half portion at ground level, meaning that over 25% of total weight of the house and nearly 50% of the school is not considered for determination of the seismic effects. This may possibly lead to underestimation of base shear. However, ELF may overestimate the maximum base shear by including the full seismic weight, as opposed to modal methods which combine 85-90% of the effective masses.

- Overestimation may be further caused by the empirical formulas for the fundamental period T_1 that are related to the building height H (**Table 21**), which for short-period buildings leads to the maximum amplification in the response spectrum (**Figure 27**).

- Another important parameter with high influence on the spectral acceleration is the structural behavior factor, generally taken as 2.0, which seems reasonable for nominally reinforced stone masonry with cement mortar. Too high values may lead to underestimation of the total base shear, especially Pakistan applies a very high behavior factor $R = 4.5$.

- Most countries (could) accept ELF, S-ELF or S-Modal for the first mode of vibration (TAJ-18), or do not require verification at all (IRN-15, CRO-11 for $a_{g,urm} < 0.30$g) for "simple regular" structures. India however requires a dynamic approach for all buildings ≥ 0.05g, which seems not in line with the concept of "non-engineered seismic design".

- Large variations are seen between the seismic hazard levels and design PGA values of the selected countries, especially at bordering areas (**Figure 25**). Overall, India and Tajikistan calculate with relatively low design accelerations, which are not based on a probabilistic approach (**Table 20**). For the calculations 0.2g was chosen as the reference PGA, which is slightly higher than the highest seismic zone value in India (0.18g), although still lower than the lowest design value in Nepal (0.25g).

- For calculation of base shear, many different values for the various applied coefficients are observed (**Table 22**). However, the resulting base shear for the house (**Table 26**) is nearly identical in Nepal, India, Afghanistan (ELF), Iran, Turkey, Croatia, and is comparable for Afghanistan (S-ELF). For the school, the differences are higher due to the high variation of importance factors.

- All base shears are calculated on rock soil. For medium and softer soil profiles, the base shear must be multiplied by a soil factor with amplifications ranging from $S = 1.15$ in EC8 to $F_a = 1.6$ in AFG-12. In Tajikistan the base shear doubles when moving from category I (rock soil) to category II.

- Base shear in Nepal closely represents the average value of all countries, whereas Pakistan is most tolerant (due to their high behavior factor) and China is most conservative (due to their high seismic coefficient). The high value of $R = 4.5$ in Pakistan is questionable and may be revised in the future, which will then result in Tajikistan being most tolerant.

- When analyzing the internal forces at the base of the masonry piers after application of the load combinations, the conclusion above does not change with just one exception; the earthquake loads in India are among the highest and match the Chinese values, due to load combination factor 1.5. Although this analysis is performed on a worst-case (less realistic) scenario for URM free-standing cantilevered piers, it is assumed that for different methods of assessing the demands, the upper and lower limits will always range between the codes of Pakistan (or Tajikistan) and China (and/or India).

- The calculated seismic loads for 0.20g in China and India, match with the Nepalese design values of 0.33g for the house and 0.30g for the school. Since Nepal allows stone masonry in areas with higher seismic hazard levels (opposed to China and India), this code is taken as the reference and starting point for further research. The Nepalese PGA values are set as targets for validation of the masonry panels, whereas other codes can be scaled accordingly by applying the percentages in **Table 26**.

To summarize, heavy-masonry-light-floor systems with negligible diaphragm action behave different under seismic excitation than most other typologies, such as frame buildings with heavy slabs. Given the observations in this chapter, the applicability of the conventional ELF, S-ELF and S-Modal methods for heavy masonry buildings is questionable. The codes however do not introduce different or modified approaches to address these differences. The implications of the above-mentioned observations, such as exclusion of large portions of seismic weight and ignoring the plinth masonry must be carefully assessed, while specific parameters for nominally reinforced stone masonry with cement mortar, such as the behavior factor, damping ratio and natural period of vibration need to be validated. Therefore, the suitability of different (possibly more sophisticated computer-aided) concepts must be analyzed, such as the equivalent frame method and distributed mass system, including an in-depth understanding of the effects of horizontal (and vertical) reinforcements. The seismic demand then needs to be checked against the ultimate capacity of the structures, for which the key lies in the determination of reliable material properties, with focus on the compression, tensile and shear strengths of the masonry, but in such way that these reflect the quality of local materials and workmanship.

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Chapter 6

Conclusions and Discussions

Summary

This thesis is the starting point and serves as an addition toward the overall objectives of the SMARTnet project. The primary research objective of the thesis is: "What is the state-of-the-art of practical seismic applications and seismic code provisions for nominally reinforced rubble stone masonry buildings with cement mortar?" The research outcomes presented in this study cover various aspects of the code specifications, the cost implications, and the seismic demand determination of rubble stone masonry buildings.

6.1 Literature Reviews of Papers, Manuals and National Codes

6.1.1 Findings and Conclusions of Chapters 1 to 3

The first part of the thesis is a global review of the state-of-the-art regarding the information and knowledge levels of rubble stone masonry buildings in seismic areas, to create an overview that shows the similarities, contradictions, gaps and differences between the publications and existing information. In total 20,500+ sessions and papers covering 16 editions of the World Conference on Earthquake Engineering (chapter 1), 47 practical field manuals between 1972 and 2017 (chapter 2), as well as 325 national seismic and masonry codes of the last 100 years (chapter 3) have been analyzed and compared, focusing specifically on "nominally reinforced rubble stone masonry (NRM) with cement mortar and wooden diaphragms in seismic areas." The findings and conclusions for all chapters are similar:

- No consistency nor consensus was found on almost all design specifications, construction guidelines and key topics, such as main dimensions, openings and reinforcing elements. The differences between the publications and the countries vary greatly, as compiled in **Tables 5, 6, 7** and **Figure 16**.

- Most information comes from just a few main sources from the 1980s, which have been altered over the years but without clear explanations or reasons. These main sources have never been properly updated, meaning that the knowledge has not evolved or progressed much since the last 40 to 50 years.

- Most manuals and codes are presented as one-size-fits-all publications which do not offer solutions that address different seismic hazard levels, or different building typologies. Even though school buildings in stone masonry are prohibited in most countries, including Nepal and India, many publications have included design specifications for schools.

- Currently, the technique of "nominally reinforced rubble stone masonry buildings with cement mortar and wooden diaphragms in seismic areas", is only allowed in 7 countries in the world: Nepal, India, China, Tajikistan, Georgia, Iran and Croatia. Several countries where rubble stone masonry is still abundantly practiced, completely rule out the technique in their codes, or have no codes in place. This is not in line with the current needs in these countries, such as in Afghanistan, Pakistan, Bhutan, Azerbaijan, Kyrgyzstan, Morocco, Tunisia, Turkey, Yemen and Albania.

- For all the above-mentioned reasons, it is concluded that the available information in the technical and practical field manuals, as well as the national seismic and masonry codes, contains many contradictions and has become ambiguous. This raises questions about their correctness, reliability and actual value.

- To enhance clarity and to avoid further confusion, it is proposed to introduce the international adoption of the term "Nominally Reinforced Masonry" (NRM) for walls that are nominally strengthened, for which Stand-Alone codes and manuals must be developed and published.

6.1.2 Proposed Improvements

6.1.2.1 Global Acknowledgment

The contextual introduction (chapter 1) shows a significant imbalance between the seismic construction needs in rural and remote areas in developing countries, compared to the level of effort that has been undertaken to improve the overall knowledge in such contexts. This imbalance is further emphasized in the reviews of chapter 2 and 3.

It is however a fact that stone masonry using local skills and resources, remains to be a predominant local structure in many developing countries in earthquake zones. This typology directly affects the lives of 217 million people in the Himalayan region alone (Nepal, India, Pakistan and Bhutan). When we include other seismically active regions where stone masonry is still in practice, such as in China, Afghanistan, Yemen, Iran, Turkey, Algeria and Georgia (to name a few), the scope of this research easily addresses an additional target group of several hundreds of millions of people worldwide.

A first important step is global acknowledgment of the current situation, for which we must ask ourselves the following key questions:
- Are we satisfied with the overall existing levels of practical and technical knowledge and information?
- Have we progressed enough since the introduction of this knowledge, more than 40 years ago?
- Do the empirical rules of thumb adequately address and fulfill today's needs for all different construction processes, contexts and settings?
- Are we offering reliable technical and practical solutions to all stakeholders, from the homeowners and self-builders to the aid industry and governmental bodies?
- On an overall note: Have we done enough for the developing countries, in which the devastation is usually highest after earthquakes?

Acknowledgment is not an easy step, as this implicates that things have not been properly or sufficiently addressed in the past. But as chapters 2 and 3 show, we have lost our grip on the basics, and if we continue to go around in circles, the knowledge level will not progress. It can even become worse given today's culture of copy-pasting and online sharing. Therefore, acknowledgment is a vital step to break the current cycle and to mark a new starting point, where we collectively agree that the current situation is no longer acceptable. And that we need to find new ways, philosophies and strategies to move forward. To underline the importance of this step, the following statement with call to action is prepared:

i) High-tech seismic design of concrete and steel structures is based on peer-reviewed scientific research and validated engineering practice. This has resulted in national and international building codes that govern the seismic resilience of such structures and which form the basis for government agencies and the construction industry.

ii) Low-tech seismic design of vernacular buildings is not based on peer-reviewed scientific research and validated engineering knowledge. It mostly relies on rules of thumb and best practice. Standards and guidelines for such structures are often outdated, contradictory and incomplete, and in the main are not fit for purpose.

iii) To properly address low-tech seismic design and construction of vernacular buildings, we must first acknowledge these shortcomings.

iv) The acknowledgment must be accompanied by the prioritization of scientific research, focused on advancing our understanding and improving the resilience of low-tech vernacular buildings in seismic events.

v) This call to action will focus on producing national and international building codes for low-tech vernacular buildings in seismic areas. These will be based on validated scientific research by means of the current state-of-the-art for calculating, testing and modeling. This work will be translated into simplified and practical seismic construction guidelines for local practitioners.

6.1.2.2 Mini-Symposium at 17WCEE

To achieve global acknowledgment and mark a new starting point, to mobilize communities and join forces to tackle the issues at hand, lots of attention and awareness will be raised for this cause. One such occasion is the organization of a Mini-Symposium at the 17th edition of the World Conference on Earthquake Engineering, to be held from September 27 to October 2, 2021 in Sendai, Japan. This Mini-Symposium brings together a balanced mix of cross-disciplinary representatives from academia, aid industries, corporate engineering, and governmental organizations of all continents. The aim is to discuss philosophies, strategies and protocols to bring the concept of “non-engineered” to the next level.

Topics include technological innovations, improved calculations and modeling, local material properties, experimental testing, code development and enforcement, technology transfer and economical aspects. The event consists of a series of short, invited talks, followed by an engaging brainstorm-session with a high audience participation. The outcome is a stimulating collaborative discussion on strategies and policies, aiming for a constructive improvement of the seismic performance of non-engineered techniques in the developing contexts, with the ultimate goal of reducing loss of life and resources. The event will be recorded, and its content can be viewed online by a larger audience.

6.1.2.3 Prioritization

A second important step is to prioritize and focus on the most urgent needs within the overall process. The focus of this thesis is on the technological side of the problem, as it is concluded that the technological level is currently not up to standard. At the same time, we cannot underestimate the need for improvements toward the dissemination of information, on-site training and code enforcement. But

for as long as the knowledge has not reached acceptable or desired levels, we must consider: What is there to disseminate in the first place? For engineers, the priority and responsibility lie in the further development and improvement of the technologies. Technology transfer, as the name implies, can only successfully follow that, when the information is up to par.

6.1.2.4 Clear Terminology

The literature reviews have brought to light that the permitted use of rubble stone masonry, as well as the specifications for stone units, are often not clearly described in the codes. This can be improved by adding extra lines in the codes, which specifically state if the technique is allowed, or not. The terminology must be clarified in terms of building typology, structural type, materialization and detailing, in order to be clear what type of structure we are designing and analyzing. The definition of the loadbearing masonry type "URM" is being perceived as misleading in earthquake engineering, as "pure" unreinforced masonry is not allowed in any of the codes. To enhance clarity and to avoid further confusion, this thesis calls for introducing a new and fourth category of masonry and proposes the international adoption of the term "Nominally Reinforced Masonry" (NRM) for walls that are nominally strengthened, next to the existing types of URM, CM and RM.

6.1.2.5 Stand-Alone Documentation

Regarding the documenting of information, several improvements are proposed. During the review of practical manuals and codes, it was noticed that the majority addresses the topic of non-engineered construction too generally, where different techniques are often mixed up. Back-and-forth paging increases the risk that information is overlooked, and more importantly, that information is misinterpreted as it is questionable whether sizes, dimensions and details can be exchanged that easily between different techniques. Some codes even refer to information that is printed outside the publication itself. Further, often no distinction is being made between higher and lower seismic levels, nor between importance of buildings for schools or houses. Such a general approach of these "one-size-fits-all" publications may result in either excessively reinforced houses in low seismic zones, or worse, in insufficiently reinforced important buildings in an area with high seismic hazard.

To avoid all the above issues, it is recommended to prepare Stand-Alone documents for each building technique separately. Adobe structures behave differently than wooden buildings, whereas block and brick masonry is different from stone masonry. And we must distinguish between stone masonry with cement mortar compared to stone masonry with mud. It is further recommended to structure the national codes for non-engineered techniques in such way, that all necessary information is found in one document. National codes should target engineers and experts and need to be made mandatory. Design and construction manuals should appeal to a wider audience of different user groups, but in all cases, the information needs to be compatible and aligned with the national codes. Regardless of the status and type of publication, they should all be upgraded with clear and exact descriptions of which technique is addressed, in terms of structural system, wall types, materials, units, mortar types and such. Clear distinctions are essential between different seismic hazards, soil classifications, building types and their implications. For each scenario, we need fully detailed designs and construction sequences, to ensure a successful implementation of the building. Which should be based on information that is validated, correct and complete according to the current state-of-the-art.

6.2 Cost Analyses and Cost Implications

6.2.1 Findings and Conclusions of Chapter 4

Chapter 4 analyzes the cost breakdown of different typologies of mountain schools and their earthquake-resistant features, regarding the techniques of rubble stone masonry and hollow concrete block masonry, as built by Smart Shelter Foundation in Nepal. The cost data spans a period of 10 years, from 2007 to 2017. It is important to note that this chapter gives no indication nor opinion about which types of wall, roof or reinforcements perform better in an earthquake; the focus is purely on the implications and the differences in cost. The following is concluded:

- As prices continuously fluctuate due to changing markets or unforeseen impacts, such as the 2015 Gorkha Earthquake, no general or useful pattern was detected that allows us to predict the situation 5 or 10 years ahead. It means that current trends and their cost implications must be constantly analyzed and updated.

- The governmental issued District Rates do not reflect variations at the micro level and are not representative for the actual situation in the hills and mountain areas, as they insufficiently address local factors such as availability of materials, transportation and accessibility to the site, or preferences of the villagers.

- To rapidly determine which construction type is cheapest to build, within any village or setting, the Bill of Quantities for 8 different school types is summarized in **Table 15**, by listing the needed quantities of materials, wages and transportation. These estimations give a very accurate and complete representation (93-97%) of the actual construction costs for these designs, for any given time frame.

- The format for rapid estimation can be adapted to other plan figurations as well. Future research includes the preparation of costing templates for housing designs, and a cost comparison between a reinforced concrete frame and a confined masonry building, based on the multi-story hostel for blind students in confined masonry as built in Nepal by Smart Shelter Foundation.

6.2.2 Safety Over Finance

An important priority should be safety over finance. The urgent need for cost-effective solutions is well understood, given the tough economic situation in many places in the world. But we must accept that safety comes with a certain price. The Nepalese government has added several alternative and cost-effective construction types to their reconstruction catalogue (vol. II), such as gabion bands and sandbags. Besides possible issues of cultural acceptance and practical implementation of such “alien” construction types, no seismic validation nor scientific justification has ever been presented to date. Even though such techniques may be beneficial in terms of cost, we need to be cautious in utilizing untested applications and unvalidated techniques.

As for more traditional construction techniques, the inclusion of horizontal bands in traditional construction types is not that expensive, at around 1.5% per band of the total construction budget. The price difference between cement and mud mortar however has an enormous impact, but it may just be the difference between survival and collapse of the building. These solutions also require further validation, but in any case, safe (and validated) solutions are recommended over cheap (and unvalidated) solutions; regardless of the fact that these solutions can or will be used on-site.

6.3 Base Shear Seismic Demand Analyses

6.3.1 Findings and Conclusions of Chapter 5

In chapter 5, full base shear seismic demand analyses with calculated examples are performed on two nominally reinforced rubble stone masonry house and school designs, as typically built in Nepal. The seismic codes are literally applied for nine countries where the technique is still allowed, being Nepal, India, China, Tajikistan, Iran and Croatia; or should be reintroduced based on current practices, such as in Pakistan, Afghanistan and Turkey. The analyses compare the base shear formulas and the inertia forces distributions of these codes, as well as material densities, seismic weights, seismic zoning, natural periods of vibration, response spectra, importance factors and seismic load combinations. Then, by following Equivalent Lateral Force-principles for Ultimate Limit State verifications ($10\%PE_{50y}$), the base shear and story shears are calculated for a design PGA of 0.20g, as well as the effects of critical load combinations on the Axial Forces (*N*), Shear Forces (*V*) and Bending Moments (*M*), acting on the lateral-resisting elements. The following is concluded:

- The case study buildings, characterized by heavy stiff walls and light flexible diaphragms, behave differently from most common structures. The main difference is that all lateral-force-generating mass is in the heavy walls, with a ratio of nearly 97.5% versus 2.5% for the diaphragms.

- The codes define conventional ways of lumping the seismic weights at floor levels and leave out the lower half portion at ground level, meaning that over 25% of the total weight of the house and nearly 50% of the school is not considered for determination of the seismic effects. This may possibly lead to underestimation of the base shear.

- On the other hand, overestimation may occur as ELF includes the full seismic weight, as opposed to modal methods which combine 85-90% of the effective masses.

- Overestimation can also be caused by the empirical formulas for the fundamental period T_1, which for short-period buildings leads to the maximum amplification in the response spectrum, and by the application of a low value for the behavior factor *R*. These factors, as well as the damping ratio ζ, need further validation for the particular typology of rubble stone masonry with cement mortar.

- Base shear in Nepal closely represents the average value of all countries, whereas Pakistan is most tolerant (because of their high behavior factor) and China is most conservative (because of their high seismic coefficient). When analyzing the internal forces at the base of the masonry piers after application of the load combinations, this conclusion does not change with just one exception; the earthquake loads in India are among the highest and match the Chinese values, because of their load combination factor 1.5.

- The calculated Nepalese design values of 0.33g for the house and 0.30g for the school, which coincide with the estimated epicentral PGA of around 0.30g during the 2015 Gorkha Earthquake, are taken as the reference and starting point for future research.

- By applying the percentages given in **Table 26**, the seismic demand and the effects of the internal forces in the masonry panels can be scaled for all other codes, in relation to the reference outputs as calculated for Nepal.

6.3.2 Future Research

6.3.2.1 Improved Calculation Models

The research outcomes presented in this thesis roughly represent the halfway point of the overall research agenda and covers various aspects of the Seismic Demand determination of rubble stone masonry buildings in seismic areas. The continuation of the research will focus on the Seismic Capacity of rubble stone masonry and validation of the case study buildings.

Heavy-masonry-light-floor systems with negligible diaphragm action behave different under seismic excitation than most other typologies, such as frame buildings with heavy slabs. Given the observations in this chapter, the applicability of the conventional ELF, S-ELF and S-Modal methods for heavy masonry buildings is questionable. The codes, however, do not introduce different or modified approaches to address these differences. The implications of the above-mentioned observations, such as the exclusion of large portions of seismic weight and ignoring the plinth masonry must be carefully assessed, while specific parameters for nominally reinforced stone masonry with cement mortar, such as the behavior factor, damping ratio and natural period of vibration, need to be validated. Therefore, the suitability of different (possibly more sophisticated computer-aided) concepts must be analyzed, such as the equivalent frame method and distributed mass system, including an in-depth understanding of the effects of horizontal (and vertical) reinforcements.

Future research, which is already underway at the time of writing of this conclusion, will address these issues in more detail. As a first step, the most realistic way of lumping the seismic masses of the case study buildings will be further investigated. The house in **Figure 24** is conservatively lumped at 2 points, being at the first-floor level and at the top of the building, whereas the masses for the school are lumped at just one point at the top. To simulate a distributed mass system, a calculation model with spreadsheets will be developed that introduces lumping points at the top position of all horizontal bands. These are situated at the top, bottom and halfway of the window openings, plus one point at the top of the building. This results in seven points for the house and four points for the school, and this method leaves out less than 10% of the seismic weight at both buildings. As a final step, we will consider the full seismic weight by assuming uniformly distributed horizontal loads among the height of the system. These are applied over the heights of the spandrels, as well as over the heights of the piers at the level of the openings. Although such approaches seem a more realistic representation for this specific building typology, the base shear will be higher due to the additional seismic weight.

Although the analyses in chapter 5 are being performed following a worst-case (less realistic) scenario for URM free-standing cantilevered piers, it is assumed that for different methods of assessing the base shear seismic demand, the upper and lower limits will always range between the codes of Pakistan (or Tajikistan) and China (and/or India). The results of the worst-case scenario with cantilevered free-standing piers (pinned-pinned connections) in chapter 5 will be compared with a best-case scenario that assumes infinitely stiff spandrels, resulting in piers that have the same height as the windows, and which are fully clamped (fixed-fixed connections). This case may closely resemble the influence of the reinforced horizontal bands that are incorporated in the masonry. However, the most realistic scenario presumably lies somewhere in the middle, for which the effective height must be determined by considering the influence of both piers, spandrels and horizontal bands.

The aim is to develop models that perform all calculations by hand as much as possible. This includes models based on the ELF method, as well as an attempt to simulate a non-linear approach which, step by step, excludes the masonry panels that have failed from the calculation sequence. At the same time, computer-generated models will be developed to compare the results with the hand calculations. Currently, students and colleagues in Italy and Portugal are developing models in different programs such as SAP2000, Tremuri, and 3DMacro.

Although it is expected that the ULS verifications are governing for heavy stone masonry buildings with light flexible diaphragms, several Serviceability Limit State (SLS) checks will be carried out at a later stage. Such as the determination of the displacements of the wall panels and the stiffness of the diaphragms. Further ULS checks such as the out-of-plane behavior of the walls will also be performed later. Out-of-plane failure is likely prevented by the horizontal reinforced concrete bands and therefore deemed not to be critical. All future results will be published in separate papers outside of this thesis.

6.3.2.2 Reliable Material Properties

To evaluate the Seismic Capacity of rubble stone masonry, we need to understand the collapse mechanisms and structural capabilities of the technique, in relation to the mechanical and strength properties of low-strength Materials, Mortars and their combined actions into wall Masonry. The material properties and mechanical characteristics of conventional building techniques, such as concrete, steel and brick masonry, are well known. They have been researched for many years and tested extensively in lab facilities all over the world, following uniform test protocols. Also, in most parts of the world, strict building codes are in place and construction workers are properly trained, to ensure that buildings meet certain standards for quality and performance. However, hand-mixed mortars and locally produced rubble stone masonry are characterized by a high variety of variables for material compositions and construction qualities. This can range from different stone types, sand grading and cement qualities, to contaminations in the water, substandard hand-mixing and proportioning in different ratios. Therefore, it is very difficult to find uniform and homogenous material properties that can be generally used for calculations and computerized modeling.

It is expected that the determination of the bond strength between mortar and stone units is a most critical parameter. If we take all the above factors into account, there are literally thousands of combinations possible, and it is impossible to test them all. Key to the research is to detect those material properties which have the highest influence on the seismic performance of rubble stone masonry. For this, an innovative approach will be developed with workable and realistic “best and worst case” scenarios that integrates parameters for local materials and regional workmanship, for which the Design of Experiments (DOE) principles will be used. To achieve uniform test results, overall test protocols based on international standards will be developed, specifically for testing of low-strength mortars and rubble stone masonry specimens. Initial tests on the strength parameters of different mortar ratios were performed in Italy during the writing of this thesis. Unfortunately, the tests for cross-checking of the outcomes were all cancelled because of the global Covid-19 situation, but it is expected that the testing and cross-checking of material properties can be resumed shortly. These results will be published in separate papers outside this thesis.

6.3.2.3 SMARTnet

To address and achieve all the above-mentioned and upcoming research objectives and tasks, a research initiative is started by the name of SMARTnet, which stands for **S**eismic **M**ethodologies for **A**pplied **R**esearch and **T**esting of **n**on-**e**ngineered **T**echniques. SMARTnet aims to update the knowledge of traditional techniques and to gain a better understanding of the seismic behavior of rubble stone masonry buildings in particular. A second aim is to make this knowledge understandable and available for engineers and non-engineers all over the globe.

The philosophy of SMARTnet requires full-time dedication and a structured, systematic and scientifically based research approach that specifically addresses vernacular and traditional construction techniques: "Non-Engineered 2.0." The aim is to significantly improve the seismic behavior of non-engineered techniques, and to fully assess, validate, optimize and complement the existing knowledge of non-engineered techniques. Because of the large number of tests to be carried out, the project envisions a global and joint approach with involvement of inter-disciplinary universities and a high student participation. This is an important strategy to cross-check data and generate large outputs, by means of the current state-of-the-art for calculating, testing and modeling, in a short time frame. As a further aim, the SMARTnet database application will be developed. This online platform will serve as a tool for communication between the stakeholders, exchange of knowledge, organizing of the research tasks, collection of data and open-source dissemination of results.

Fact is, that several hundreds of millions of people continue to live in stone houses in South and Central Asia, the Middle East, Northern Africa and Europe as well. They are in need of clear and reliable information that is up-to-date and complete. It is expected that a full validation and justification of the seismic behavior of rubble stone masonry buildings will strengthen the confidence in those countries that still use this technique, as well as create renewed interest in countries that currently prohibit it. Therefore, SMARTnet issues an international call (such as at 17WCEE) and invites experts, professionals, academics and final-year students in all relevant fields to exchange their knowledge, and to support the project with their time and expertise. Aiming to reduce the of loss of life, as well as reducing of financial losses in seismically prone (developing) countries, by reducing the risk of damage and collapse of indigenous, traditional, and non-engineered buildings.

Appendix A

Questionnaire for Detailed Pricing of Material, Labor and Transportation Costs in Nepal - In English and Nepali

Notes on what to look for and how to conduct this survey

The aim is to get as detailed information on prices of building materials as possible. This includes:
-The material itself
-The unit in which this material comes
-Additional costs for hauling, carrying and transport, if any.

Example 1 for sands, stones and pebbles.
Sand or pebbles generally come from a local river, and the price is mostly given as a total price per volume (m3, cft) or per truck load, or something else (sometimes stones are given per chhatta…). Always make sure to know what unit they use.

Secondly, it is most important to know what this total price includes.
Is hauling and filling of sacks included? Is the carrying from river to village included?
If it is per truck, we not only need to know the price per trip, but also if loading and unloading is included.
And important is to know the volume per each truck load.

If the village cannot break-down these costs exactly, it is fine. For as long as we are certain everything is included in this total price. However, if they can break it down, that is appreciated for a more accurate estimate.

Extra note about sand:
We must be certain that the right sand comes from the right river.
When the sand is coarse it is perfect for concreting. But if this same river has no fine sand, we need to get the fine plastering sand from another river. Meaning the transport costs will be higher. This must be taken into account.

Example 2. Wood work.
In many cases the village has their own community forest, from where the wood is cut. Not sure if this is still the case after the earthquake, as wood may become scarce.
So we need to know where the wood comes from, and what kind of wood they use (Sal?).
Community forest wood is basically considered to be free, and only milling or carpenter charges are calculated.

A very helpful figure is the milling rate, usually per cft, but can be m3, or other. But then it is important to know what is included in this: cutting, transport to mill, transport back to village etc.
If possible, try to find local rates for full element, such as door and window frames, doors and window shutters. What is included; making by carpenters, bolts and hinges, fitting?
Try to find out prices of door and window sets (bolts, hinges etc.) separately.
If possible, can they give rates of certain wood dimensions per Lineal foot (Lft) or cft/m3?
And if possible rates for elements in square meter or square feet, for ceiling, shuttering, valance board

Example 3. Materials to be purchased from outside.
Many materials must be bought in the market, such as cement, steel, tin sheets and such.
In this case for sure transport and carrying are to be included.
Important: Please ask for separate prices: bag + transport + carrying (if any)
kg of steel + tractor load + carrying etc.

Example 4. Miscellaneous Materials
Certain materials you may not use in your building. Perhaps you don't build with hollow cement blocks, or steel roofing pipes.
Still, can you try to find rates for all items, at this will still help me with preparing, comparing and creating a full picture of rates and prices all over Nepal.

यो सर्भे कसरी गर्ने र के का लागि गर्ने भन्ने वारे संक्षिप्त जानकारी ।
यस सर्भेको उदेश्य निर्माण सामाग्रीहरुको सम्भव भए सम्मका मुल्य र विवरणहरु प्राप्त गर्नु हो । जस्मा तलका मुख्य विषयहरुका वारेमा जानकारी संकलन गरिनेछ ।
- निर्माण सामाग्रीको वारेमा
- निर्माण सामाग्री नापिने इकाईका वारेमा
- यातयात, वोक्ने, मिसाउने आदीको थप मुल्यको वारेमा र यदी अरु कुनै भएमा

उदाहरणको लागि १, वालुवा, ढुंगा र गिट्टीको लागि
वालुवा वा गिट्टी साधारणतया स्थानिय नदी वा खोलाबाट ल्याइन्छ र तिनीहरुको मुल्य नापको आधारमा क्युविक मिटर वा फिटमा अथवा प्रति ट्रक वा ट्याक्टर वा अरु यस्तै (कहिले काही ढुंगालाई चट्टामा नापिन्छ)
कुन नापबाट नापिन्छ , निश्चत गर्ने ।

दोश्रो , उक्त मुल्यमा के के चिजको मुल्य समावेस छन भन्ने कुरा महत्वपुर्ण हुन्छ ।
के छान्ने, भर्ने आदीको मुल्य समावेस छ ? के खोला देखी गॉउसम्मको यातयात समावेस छ ? यदी ट्रकबाट सामाग्री ल्याउदा , हामीलाई प्रति टिपको मुल्य थाहा भएर भएन तर सामाग्री लोड गर्ने र झार्नेको मुल्य समावेस छ की छैन र एक ट्रकमा कतिमात्रामा सामाग्री आउछ थाहा पाउनु महत्वपुर्ण हुन्छ ।

यदी सवैकुरा छुट्याउन सकिदैन भने केही छैन तर कुल मुल्यमा सवै चिजहरुको मुल्य समावेस छ कि छैन निश्चित हुनु पर्छ । जे भए पनि, छुट्याउन सकिन्छ भने सही लागत निकाल्न सहयोग पुग्ने छ ।

वालुवाको वारेमा थप जानकारी
हामीले यो निश्चित गर्नु पर्छ कि उपयुक्त(राम्रो) वालुवा कुन खोलामा पाइन्छ ?
खस्रो वालुवा ढलानका लागि र मसिनो वालुवा प्लाष्टरको लागि उपयुक्त हुन्छ यी दुवै वालुवा एउटै नदीमा नपाइन सक्छ जस्को कारण यातयात खर्च कम वा वढी हुन सक्छ। यस्को वारेमा ध्यान दिनु पर्ने हुन्छ ।

उदाहरण २ - काठको काम
धेरै ठॉउमा स्थानिय सामुदायिक वनबाटै काठ काटिन्छ । तर भुकम्प पछि यस्तो स्थिती छ , कि छैन थाहा भएन । सर्वप्रथम कुन काठ प्रयाग गर्ने (साल ?) र कहॉबाट काट्ने भन्ने निश्चित गर्ने । साधारणतया स्थानिय वनबाट रुख नि शुल्क पाइने प्रचलन छ भने त्यो रुख काट्न र सिकर्मीको खर्च काठको मुल्यमा जोड्नु पर्छ ।

काठ चिर्दा प्रति घनफिट , घन मिटर वा अन्य इकाई थाहा पाउन सकिएमा उपयोगी हुने थियो । काठको मुल्यमा रुख काट्ने, मिल सम्म लैजाने, मिलबाट गाउसम्म लैजाने सवै खर्च समावेश गर्नु पर्छ । सम्भव भए सम्म ढोका, झ्यालका फ्रेम, खापा आदीको स्थानिय मुल्य का साथै सिकर्मी खर्च, नट वोल्ट, गजवार, छेस्कनी आदीको मुल्य पनि समावेश गर्नुपर्छ ।
झ्याल र ढोकाका सेटहरुको मुल्य **छुट्टाछुट्टै** पत्ता लगाउनुपर्छ ।

उदारण ३ , वाहिरबाट खरिद गर्नु पर्ने सामाग्रीहरु
धेरै निर्माण सामाग्रीहरु वजारबाट खरीद गर्नु पर्ने हुन्छ जस्तै सिमेन्ट, रड, टिन आदी
यसमा ढुवानी खर्च र वोक्ने खर्च आदी समावेस भएको हुनुपर्छ ।
महत्वपुर्ण : कृपया **छुट्टाछुट्टै** मुल्य उल्लेख गर्नुहोस, सिमेन्ट प्रति वोरा + ढुवानी +वोक्ने (अन्य कुनै भएमा)आदी
रड प्रति केजी+ ढुवानी आदी

उदाहरण ४ , विविध सामाग्रीहरु
केही निर्माण सामाग्रीहरु त्यहॉ प्रयोग हुदैनन जस्तै सिमेन्ट व्लक, ट्रस पाइपहरु आदी तर पनि तिनीहरुको पनि मुल्य थाहा पाउन पाए नेपालका विभिन्न स्थानहरुको दर रेट तयार गर्न , तुलना गर्न र एउटा पुर्ण दररेट निकाल्न सहयोग पुग्ने थियो ।
धेरै धेरै अग्रिम धन्यवाद ।

Village Location:गाउँको भौगिलक अवस्था: Contact Person in village + phone no:

Village name &VDC-ward: गाउको नाम र गाउपालिका-वडा नं:		District: जिल्ला:
Altitude of the village: गाउको उचाई :		Area: (plain, hill, mountain, remote) क्षेत्र:(समथर, हिमाली, पहाडी , दुर्गम)
Accessibility to village यातयातको अवस्था	accessible by: (bus, jeep, tractor, mule, foot) यातयातको किसिम: (वस, जिप, ट्याक्टर, खच्चड , पैदल)	
Walking distance from village to nearest road नजिकको मोटरबाटो बाट गाउ सम्म पुग्न पैदलको समय:	in km: कि.मि.मा :	in time: लाग्ने समय:
Distance to nearest Chowk नजिकको वजार	in km: कि.मि.मा	nearest city: नजिकको वजार :
Name and distances to nearest rivers नजिकको नदीको नाम र दुरी	for rough sand & pebbles: खस्रो वालुवा र गिट्टीको लागि: कि.मि.मा :	for fine plastering sand प्लाष्टर वालुवा को लागि: कि.मि.मा :

General Information:सामान्य जानकारी:

Site clearing निर्माण स्थल सफा गर्ने	Total cost of clearing, leveling & preparing of land for construction: निर्माण स्थल सफा गर्ने, सम्म्याउने र तयार गर्ने जम्मा खर्च :
What main materials are proposed for the building भवनको लागि प्रयोग गरिने सामाग्रीहरु को विवरण	Foundation: (eg. mud or cement, mountain or river stones etc.) जग: (माटो वा सिमेन्ट, स्थानिय ढुंगा वा नदीको ढुंगा आदी)
	Walls: (stones, bricks, mud, cement etc.) गाह्रो : (ढुंगा, इट्टा, माटो , सिमेन्ट आदी)
	Roof: (wood or steel) छाना: (काठ, फलाम)
	Woodwork: (Sal, other) काठको काम: (साल वा अन्य)

Materials Rates, Units and Weights:सामाग्रीहरुको दर , इकाइ र तौलः

Soling stones (from where?) सोलिङ गर्ने ढुंगा	price per unit: प्रति इकाइ मुल्यः	Where are the stones from? And is price incl. hauling /carrying / transport? ढुंगा काहाँवाट ल्याइन्छ? र भिक्ने, ढुवानी , वोक्ने आदी मुल्य ?		
	unit: (m3, cft, sack…) इकाईः (घन मिटर, घन फिट, वोरा वा अन्य)	if not, cost of transport per load यदी होइन भने प्रति ट्याक्टर वा ट्रकको मुल्यः	if not, hauling charge per unit भिक्ने मुल्य प्रति इकाई	if not, carry charge per unit वोक्ने मुल्य प्रति इकाई
Mountain stones or River stones (which one, and from where?) स्थानिय ढुंगा वा नदीको ढुंगा(कुन र कहाँबाट)	price per unit: प्रति इकाइ मुल्यः	Where are the stones from? And is price incl. hauling /carrying / transport? ढुंगा काहाँवाट ल्याइन्छ? र भिक्ने, ढुवानी , वोक्ने आदी मुल्य ?		
	unit: (m3, cft, sack…) इकाईः (घन मिटर, घन फिट, वोरा वा अन्य)	if not, cost of transport per load यदी होइन भने प्रति ट्याक्टर वा ट्रकको मुल्यः	if not, hauling charge per unit भिक्ने मुल्य प्रति इकाइ	if not, carry charge per unit वोक्ने मुल्य प्रति इकाइ
Rough construction sand for concretes & mortars (from which river?) खस्रो वालुवा ढलान र गाह्रोका लागि	price per unit: प्रति इकाइ मुल्यः	Where is the sand from? And is price incl. hauling /carrying / transport? ढुंगा काहाँवाट ल्याइन्छ? र भिक्ने, ढुवानी , वोक्ने आदी मुल्य ?		
	unit: (m3, cft, sack…) इकाईः (घन मिटर, घन फिट, वोरा वा अन्य)	if not, cost of transport per load यदी होइन भने प्रति ट्याक्टर वा ट्रकको मुल्यः	if not, hauling charge per unit भिक्ने मुल्य प्रति इकाइ	if not, carry charge per unit वोक्ने मुल्य प्रति इकाइ
Pebbles 3/4” aggregate for concretes (from which river?) ढलानको लागि गिट्टी 3/4"को	price per unit: प्रति इकाइ मुल्यः	Where are the Peebles from? And is price incl. hauling /carrying / transport? गिट्टी काहाँवाट ल्याइन्छ? र भिक्ने, ढुवानी , वोक्ने आदी मुल्य ?		
	unit: (m3, cft, sack…) इकाईः (घन मिटर, घन फिट, वोरा वा अन्य)	if not, cost of transport per load यदी होइन भने प्रति ट्याक्टर वा ट्रकको मुल्यः	if not, hauling charge per unit भिक्ने मुल्य प्रति इकाइ	if not, carry charge per unit वोक्ने मुल्य प्रति इकाइ
Fine sand for plastering (from which river?) प्लाष्टरको वालुवा	price per unit: प्रति इकाइ मुल्यः	Where is the sand from? And is price incl. hauling /carrying / transport? वालुवा काहाँवाट ल्याइन्छ? र भिक्ने, ढुवानी , वोक्ने आदी मुल्य ?		
	unit: (m3, cft, sack…) इकाईः (घन मिटर, घन फिट, वोरा वा अन्य)	if not, cost of transport per load यदी होइन भने प्रति ट्याक्टर वा ट्रकको मुल्यः	if not, hauling charge per unit भिक्ने मुल्य प्रति इकाइ	if not, carry charge per unit वोक्ने मुल्य प्रति इकाइ

Materials Rates, Units and Weights:सामाग्रीहरुको दर , इकाइ र तौलः

Pebbles 1/2” aggregate for grouting (from which river?) सानो 1/2" को गिट्टी	price per unit: प्रति इकाइ मुल्यः	Where are the pebbles from? And is price incl. hauling /carrying / transport? गिट्टी काहाँवाट ल्याइन्छ? र भिक्ने, ढुवानी , वोक्ने आदी मुल्य ?		
	unit: (m3, cft, sack…) इकाईः (घन मिटर, घन फिट, वोरा वा अन्य)	if not, cost of transport per load यदी होइन भने प्रति ट्याक्टर वा ट्रकको मुल्यः	if not, hauling charge per unit भिक्ने मुल्य प्रति इकाइ	if not, carry charge per unit वोक्ने मुल्य प्रति इकाइ
Cement (50 kg) सिमेन्ट (५० केजी)	price per bag: प्रति वोरा मूल्यः	which brand and which grade? कति ग्रेड र कुन ब्राण्डको ?		
	where to buy? कहाँ किन्ने ?	transport charge from chowk / load ढुवानी मुल्य प्रति टिप	how many kg per each load? कति केजी प्रति टिप?	carry rate from road, per bag वाटोबाट वोक्ने मुल्य प्रति वोरा ?
Local mud for mortar (from where) माटो मुछेर गाह्रा लगाउनको लागि	price per unit: प्रति इकाइ मुल्यः	Where is the mud from? And is price incl. hauling /carrying / transport? माटो काहाँवाट ल्याइन्छ? र भिक्ने, ढुवानी , वोक्ने आदी मुल्य ?		
	unit: (m3, cft, sack…) इकाईः (घन मिटर, घन फिट, वोरा वा अन्य)	if not, cost of transport per load यदी होइन भने प्रति ट्याक्टर वा ट्रकको मुल्यः	if not, hauling charge per unit भिक्ने मुल्य प्रति इकाइ	if not, carry charge per unit वोक्ने मुल्य प्रति इकाइ

Steel rods for reinforcements (per kg) रड प्रति किलो	12 mm: (TOR) १२ एम एम टोर	10 mm: (TOR) १० एम एम टोर	.. mm: (other) …. एम एम अन्य
	7 mm: (TOR) ७ एम एम टोर	6 mm: (plain) ६ एम एम सादा	Binding wire: वाइन्डीग तार
	cost of transport per load प्रति टिप मुल्य	where to buy? कहाँ किन्ने?	carry charge to village/unit गाउँसम्म ल्याउने मुल्य प्रति इकाईः

Materials Rates, Units and Weights: सामाग्रीहरुको दर , इकाइ र तौल:

Tin sheets for roof (per bundle) छानाको लागि टिन (प्रति वण्डल)	high quality 26 gauge, 0.41 mm, blue: २६ गेजको गुणस्तरीय ०.४१ एम एमको निलो		less quality sheets, silver: सामान्य गुणस्तरको टिन:	
	where to buy? कहाँ किन्ने ?	cost of transport per load प्रति टिप यातयात मुल्य	how many kg per each load? कति केजी प्रति टिप?	carry charge to village per unit गाउँसम्म ल्याउने मुल्य प्रति इकाई:
	on wood or steel frame? काठको फ्रेम वा फलामको ?	roofing nails per kg: (on wood) छानाको लागि काँटी प्रति केजी (काठको लागि)	J-hooks per pcs or kg: (on steel frame) छानाको लागि जे हुक प्रति केजी वा प्रति गोटा:(फलामे ट्रसको लागि)	

Wood in general (what wood is used?) काठको लागि (के काठ प्रयोग गरिन्छ ?)	does the village have community forest? समुदायको आफ्नै वन छ ?		if not, where to buy? छैन भने कहाँ किन्ने ?	
	wood used for trusses and roof? छानाको लागि वा ट्रसको लागि काठ प्रयोग गरिन्छ?	wood used for doors & windows? ढोका वा झ्यालको लागि काठ प्रयोग गरिन्छ?	for finishing and valance boards? फिनिसिगमा पनि काठ प्रयोग गरिन्छ?	shuttering? खापाहरु पनि ?
Price determination of wood in village गाँउमा पाइने काठको मुल्य निर्धारण ।	general wood price: काठको साधारण मुल्य:	If wood is free, what is milling cost& per what unit? यदी काठ निशुल्क हुन्छ भने त्यसको चिरानी मुल्य कति होला र के को आधारमा हुन्छ ?		
	unit:(m3, cft, Lft) इकाइ:(मिटर, फिट)	Place and distance of mill? स मिल भएको स्थान र दुरी ?	Transport cost to mill and back?समिल सम्म लैजाने र ल्याउने यातयात खर्च?	

Materials Rates, Units and Weights:सामाग्रीहरुको दर , इकाइ र तौलः

Local Wood prices per element (if known) स्थानिय काठको मुल्य प्रति गोटा (यदी थाहा छ भने)	beam 4"x5" for roof trusses 4"x5" को ट्रस वनाउने काठ	price: मुल्यः	what unit:(m3, cft, Lft) नाप्ने इकाईः घन मिटर, घन फिट)
	beam 4"x3" for roof trusses 4"x3" को ट्रस वनाउने काठ	price: मुल्यः	what unit: (m3, cft, Lft) नाप्ने इकाईः घन मिटर, घन फिट)
	size 2"x4" for rafters 2"x4" को भाटा वनाउने काठ	price: मुल्यः	what unit: (m3, cft, Lft) नाप्ने इकाईः घन मिटर, घन फिट)
	planks 1"x9" for valance boards and cladding 1"x9" को फलिका	price: मुल्यः	what unit: (m3, cft, Lft) नाप्ने इकाईः घन मिटर, घन फिट)
	(other) अन्य	price: मुल्यः	what unit: (m3, cft, Lft) नाप्ने इकाईः घन मिटर, घन फिट)
	full door frame 7 x 3 feet of wood 3"x4" 3"x4" को काठको ७x ३ फिटको ढोकाको फ्रेम	price: मुल्यः	per complete frame प्रति फ्रेम
	full door panel apprx. 7x3 ft. 1.5" thick 1.5" वाक्लो काठको ७x ३ फिटको ढोकाको खापा	price: मुल्यः	per complete door प्रति खापा
	full window frame 4 x 5 feet of wood 3"x4" 3"x4" को काठको ४ x ५ फिटको झ्यालको फ्रेम	price: मुल्यः	per complete frame प्रति फ्रेम
	two shutters apprx. 2 x 5 ft. 1.5" thick 1.5" वाक्लो काठको २x ५ फिटको २ खापाहरु	price: मुल्यः	per set of shutters प्रति सेट खापाहरु

Materials Rates, Units and Weights:सामाग्रीहरुको दर , इकाइ र तौलः

Other woods and wood accessories अन्य काठ र यसका सहायक सामाग्री	shuttering wood खापाको काठ	price: मुल्यः	what unit: (cft,m2, sq.ft, Lft) नाप्ने इकाईः वर्ग मिटर, वर्ग फिट)
	triplex board for ceiling सिलिगको लागि प्लाइ उड	price: मुल्यः	what unit:(m2, sq.ft) नाप्ने इकाईः वर्ग मिटर, वर्ग फिट
	Nails, any size कांटी, को साइज	price: मुल्यः	per kg प्रति केजी
	Door set of tower bolts, hinges, locks, handles etc. ढोकाको लागि कब्जा, हेण्डल, ताला चावी आदी	price: मुल्यः	per complete set सम्पुर्ण सेटको लागि
	Window set of tower bolts, hinges, locks, etc. झ्यालको लागि कब्जा, छेस्कनी, हेण्ड आदी	price: मुल्यः	per complete set सम्पुर्ण सेटको लागि
	Galvanized steel wire 4 mm for connecting trusses ट्रसहरु बाँध्नको लागि ४ एम एम ग्याविन तार	price: मुल्यः	Unit:(Lft or kg) इकाईः मिटर, फिट वा केजी)

Steel pipes for roofing frame (as alternative for wood) फलामको पाइप छानाको लागि (काठको विकल्पमा)	truss pipes2" diameter for top and rafters ट्रसको लागि २ इन्चको पाइप	price: मुल्यः	unit:(Lft, ...) इकाईः फिट
	truss pipes0.75" diameter for battens ०.७५ अर्धव्यासको ट्रस पाइप	price: मुल्यः	unit:(Lft, ...) नाप्ने इकाईः फिट
	10 gauge binding wire for connections १० गेजको वाइन्डीग तार	price: मुल्यः	per kg प्रति केजी
	J-hooks with bolts जे हुक	price: मुल्यः	unit:(pcs, kg) नाप्ने इकाईः (प्रति गोटा वा केजी)
	anchors to connect trusses to top beams टप विम मा ट्रससंग वाध्ने एंकर	price: मुल्यः	unit: (pcs, kg) नाप्ने इकाईः (प्रति गोटा वा केजी)

Materials Rates, Units and Weights:सामाग्रीहरुको दर , इकाइ र तौलः

Miscellaneous items अन्य विविध	white cement for whitewashing walls वालहरुमा लगाउने सेतो सिमेन्ट	price: मुल्यः	Per 50 kg bag प्रति ५० केजी वोरा
	primer for painting wood काठमा लगाउने प्राइमर	price: मुल्यः	unit:(liter, can) इकाइः (लिटर , वट्टा)
	paint for wood work, doors & windows, cladding etc. झ्याल , ढोका वा अन्य काठमा लगाउने पेन्ट	price: मुल्यः	unit: (liter, can) इकाइः (लिटर , वट्टा)
	(other) अन्य	price: मुल्यः	unit: इकाइः
	(other) अन्य	price: मुल्यः	unit: इकाइः

Labour wagesकामदार ज्याला

unskilled labour for digging, hauling, carrying, mixing etc. अदक्ष मजदुर खन्ने , वोक्ने, मिसाउने आदी	rate per day: प्रति दिन ज्यालाः
skilled mason दक्ष डकर्मी	rate per day: प्रति दिन ज्यालाः
steel bar-bender डण्डीको काम गर्ने दक्ष कामदार	rate per day: प्रति दिन ज्यालाः
skilled carpenter दक्ष सिकर्मी	rate per day: प्रति दिन ज्यालाः
steel welder फलाम वल्डीगं गर्ने कामदार	rate per day: प्रति दिन ज्यालाः
painter रंग लगाउने कामदार	rate per day: प्रति दिन ज्यालाः
(other) अन्य	rate per day: प्रति दिन ज्यालाः

Further Comments (if any)यदी केही सुझाव भएमा

Thanks to all participants for their time and cooperation यहाँहरुको समय र सहयोगको लागि धेरै धन्यवाद ।