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主　論　文　の　要　旨

論文題目　SOIL-WATER COUPLED FINITE DEFORMATION ANALYSIS ON QUASI-SEISMIC/SEISMIC WAVE PROPAGATION INSIDE SOIL SPECIMEN AND MULTI-LAYER GROUND（土供試体および多層系地盤内の波動伝播特性に関する水～土骨格連成有限変形解析）

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論　文　内　容　の　要　旨

In this thesis, employing a quasi-static/dynamic soil-water coupled finite deformation FEM code, there are mainly three aspects to be studied, which includes the new application of numerical calculation in hollow torsional test, analysis of generation of quasi-seismic wave during strain localization (fault-like deformation) inside the soil specimen and characteristic of seismic propagation in the multi-layer ground as well as its influence on the existing upper structures.

In *Chapter 1*, the research background is firstly presented. It is usually regarded that the initiation of observed seismic waves near the ground surface comes from the slippage of faults or the movement at the interface of earth crusts in the form of localized deformation. Relying on the experiments of acoustic emission, the previous researches aimed to explain such sudden energy release by acoustic emission signals and tried to monitor some man-made microseismics. However, such signals cannot represent the characteristics of wave motion such as predominant period, maximum amplitude. It seems to be a reasonable method to use continuum mechanics to capture the significant changes during the formation of strain localization. But in the previous analyses about shear band, the occurrence of shear band is often based on an initially uniform deformation field and the inertia forces are usually neglected. Therefore, the focus is mainly put on the reason of seismic wave generation and its damages the urban lifeline system, which makes it necessary to acquire a deeper interpretation of the generation and propagation of seismic waves and to carry out more precise prediction of seismic responses. Then research objective and scope are given. The thesis firstly aims to develop a rigorous three-dimensional hollow torsional test as a new application of the FEM code by treating the soil specimen as an initial-boundary value problem, which is very rare in the previous researches. It is very meaningful for further study on the deformation/stress characteristic in complicated stress paths. Secondly when taking the inertia term into consideration, the collapse of uniformity in deformation field (or reason of occurrence of strain localization) and the generation of quasi-seismic waves during the localized deformation are the second point that the thesis desires to clarify. Here, acceleration waves are “actively” generated inside the analysis domain, which is different from the usual dynamic computations such as liquefaction analyses where the acceleration waves are “passively” prescribed. It would provide a new aspect to interpret the formation of faults and the mechanism of the earthquake. Thirdly, a seismic stability of a signal-receive panzer mast is evaluated, during which the influences of ground layer composition and ground layer sequence on the liquefaction possibility and seismic response of upper structure are discussed in detail. It provides a more precise prediction of seismic response since the difference in the stratigraphic composition along the depth is rarely taken into consideration in the conventional liquefaction judgment. At last, the brief introduction of the FEM code—*GEOASIA* and the outline of the thesis are presented.

In *Chapter 2*, “Fitting” that determines the soil parameters and initial values is explained in detail. For the triaxial and oedometer results of undisturbed clay specimen, the completed stress paths including the drilling, sampling and loading are reproduced faithfully based on numerical calculation of SYS Cam-clay model. By try-and-error adjustments, a group of soil parameters and a group of initial values are finally obtained. If there are no laboratory experimental results, the survey datum such as specific volume and unconfined strength for clay and N-value for sand are often used to predict the soil parameters. The accuracy of numerical calculation is greatly influenced by this process.

In *Chapter 3*, initially the verification of FEM code is carried out. The thesis firstly, based on the $\boldsymbol{u}$-p formulation for a saturated soil that satisfied the element-wise undrained/constant-volume condition, desires to reproduce the uniform deformation field when the inertia forces are considered and to reveal the reason of the collapse of uniform deformation. A quasi-static/dynamic soil-water coupled finite deformation FEM code *GEOASIA*, in which a sophisticated elastoplastic constitutive model called SYS Cam-clay model is incorporated is utilized in the calculation. By applying initially distributive velocity and acceleration, the loading rate and the permeability coefficient which have a great influence on the migration of pore water are found to be important in the maintenance of uniformity. The pore water pressure should be convexly distributive with respect to the inertia term. Such verification is necessary for the code when it is extended from quasi-static to dynamic and it also proves its high performance in delicate calculations. When there are no distributive values, the loading rate and loading method which are irrelative in the quasi-static analysis show significant influences on the deformation patterns. Tremendous impact-induced acceleration waves are observed inside the specimen, which has affected the geometrical deformation, excess pore water pressure and deviator stress in the apparent behavior. In the next, the dynamic soil-water coupled strain localization analysis is carried out to clarify the information of acceleration waves during localized deformation, which may help to figure out the natural seismic waves and acoustic emission signals in the experiment. In order to get a single fault-like shear band, an initial geometrical imperfection is introduced into the side boundary of the specimen. Consequently, there are two types of acceleration waves obtained in the analysis: the impact-induced acceleration waves as mentioned above and the localization-induced acceleration waves accompanying the formation of shear band. The impact-induced waves are of greater magnitude and smaller predominant period, which is quite different from the subsequent waves due to localized deformation and is very easy to distinguish one from the other. The localization-induced waves, with the same order of magnitude as measured near the ground surface and longer predominant period compared with impact-induced waves, consist of not only the waves themselves but also their reflections at the boundary, which makes it very difficult to distinguish them. In addition, the effects of time increment and mesh length are investigated in detail. It is found that the CFL condition is not necessary in the calculation because of the implicit time scheme and the waves with higher frequency can be captured as the time increment and mesh length become smaller. But the predominant period is independent of the time increment and mesh length. When the effects of initial confining pressure and overconsolidation ratio which affect the stiffness of the specimen are considered, due to the influence of reflections in the localization-induced waves, the predominant period becomes smaller as the stiffness of the specimen increases. When the loading method is changed from displacement control to stress control, the evolutional rate the shear band seems to be quite different although the shape of shear band is similar. Consequently, the localization-induced acceleration waves behave quite different, with a higher magnitude and higher predominant frequency.

In *Chapter 4*, as a new application of *GEOASIA*, a three-dimensional hollow cylinder test is then treated as an initial-boundary value problem to bridge the gap of numerical calculations besides the axial-symmetry, plane strain and triaxial three-dimensional conditions. Compared with past researches, the present study takes three-dimensional condition, elastoplastic constitutive model, soil-water coupled effect and inertia force into consideration. Taking comparison between experimental and numerical results, the non-uniformities in shear strain, excess pore water pressure and overconsolidation ratio etc are shown clearly. The influence of specimen geometries including wall thickness, heights and outer diameters on the non-uniformity is investigated in detail. A new evaluation method of the non-uniformity for three-dimensional condition is proposed to judge the non-uniformity continuously. It is found that thinner wall thickness, larger height and greater outer diameter is able to decrease the non-uniformity inside the specimen. The influence of no-uniformity on the apparent behavior of the specimen is investigated by comparing with the "perfect path", which represents the response of soil with the same boundary conditions under a uniform deformation field. Slight differences concerning excess pore water pressure and deviator stress in the apparent behavior are caught, which could be acceptable to some extent. Also there should be a critical height to prevent failure at the specimen ends according to the apparent behavior. At last, experiments under torque control is numerically carried out by the "no-length change" and "no-angle change" conditions and the number of installed rigid ribs in practical experiments is discussed, in which it is found that 4 ribs could not transfer the torque reliably while 6 or 8 ribs are feasible.

In *Chapter 5*, a high-precision seismic response of urban lifeline structure—panzer mast that controls the gas supply/stoppage remotely is carried out employing *GEOASIA*. One of the features of the study is solving the ground deformation during and after the earthquake simultaneously once the state of ground is determined initially. It can be applied from ground deformation until failure and can be used to analyze co-seismic behavior over a time range of a few seconds to a few minutes and post-seismic behavior, in which case the time range is from a few years to a few centuries. The ground compositions and sequences are taken into consideration to give a more accurate judgement of liquefaction and to investigate the propagation characteristic of seismic waves. In the evaluation of seismic stability of the steel column, the dynamic soil-structure interaction is also considered since the existing equipment itself satisfies the design criteria of the massive earthquake. It is found that although the acceleration waves attenuate greatly in a liquefied layer, there is still a hazard of topple-over due to the loss of bearing capacity in the liquefiable layer when the embedded depth is not enough. Contrarily, even though the acceleration waves amplify significantly in the clay layer, the panzer mast only oscillates greatly without excessive inclination. Moreover, even when the soil of the surface layer on which the structure installed is same, the seismic stability of the structure varies greatly depending on the differences in the stratigraphic composition (sequence and thickness of layers). In particular, when there is a thick deposit of weak clay below a liquefiable layer but the thickness of a liquefiable surface layer is small, the stability of the structure above is significantly reduced. It should be pointed out that the influence of the difference in the stratigraphic composition along the depth is rarely taken into consideration in the conventional liquefaction judgment.

In *Chapter 6*, the main conclusions and further works are summarized.

There are totally 17 Appendixes. In *Appendix 1*, a brief introduction of continuum mechanics is introduced. *Appendix 2* gives a specific description of SYS Cam-clay model and the concrete form SYS Cam-clay constitutive matrix is shown in *Appendix 3*. The constitutive response of SYS Cam-clay model under a uniform deformation field is presented in *Appendix 4* for various loading conditions. *Appendixes 5-9* introduce the theoretical principle of mixture theory and application of finite deformation method in *GEOASIA*. *Appendix 10* gives the linear constraint conditions using Lagrangian method. *Appendix 11* shows the corresponding relationship of initial values in SYS Cam-clay model. *Appendix 12* illustrates how to determine the initial state in the ground. *Appendix 13* gives the application of viscous boundary condition into FEM. *Appendixes 14-17* give the required equations of hollow cylinder test and *Appendix 18* shows the uniqueness of solution in quasi-static and dynamic analysis.