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主　論　文　の　要　旨

論文題目　Large Deformation of Highly Compressible Peaty Ground under Embankment Loading and a Proposal/Application of New Macro Element Method for Simulating Vertical Drain/Vacuum Consolidation(盛土載荷に伴う高圧縮性ピート地盤の大変形と鉛直ドレーン／真空圧密シミュレーションにおける新しいマクロエレメント法の提案／適用)

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論　文　内　容　の　要　旨

In the view of engineering, infrastructure development such as embankment construction on soft ground including highly compressible clay/peat could be considered one of the most difficult and stimulating tasks. Numerous damages due to unexpected circumstances such as long-term settlement, differential settlement and slip failure have been reported in this type of ground. In order to avoid potential damages, pre-countermeasures such as ground improvement are important to increase ground stability and reduce residual settlements. Vertical drain method has often been used as an effective pre-construction countermeasure for soft ground, and the representative examples are; the sand drain method and prefabricated (plastic-board) vertical drain method. In recent years, vertical drain method combined with vacuum consolidation method has been widely applied especially when embankments have to be constructed quickly to shorten construction period or when very soft soils such as peat exist near the ground surface. In practical design of vertical drains, one-dimensional consolidation calculation based on Barron's theory has been widely used, and in case of combining vacuum consolidation, the reduction in pore water pressure due to vacuum loading is often replaced by an equivalent surcharge load for simplification. However, in order to account for the inward deformation characteristics of vacuum consolidation, it is desirable to perform finite element analysis in multiple dimensions. In multi-dimensional finite element analysis, directly representing the vertical drain by finite elements with high permeability requires a considerable number of elements. Therefore, a macroscopic method is needed to describe the improved effects of installing vertical drains depending on drain spacing and permeability. In addition, a suitable analysis code was requested to describe the mechanical behavior of naturally deposited soft ground considering the range of behavior from large delayed settlement to instantaneous circular slip failure.

This study investigates numerically behaviors of soft ground including highly compressible peat under embankment loading improved by vertical drain/vacuum consolidation using soil-water coupled finite deformation analysis code ***GEOASIA*** based on an equation of motion with an inertial term, onto which the SYS Cam-clay model was mounted as an elasto-plastic constitutive equation describing the soil skeleton structure. In regard to macroscopic methods, this study employs a newly proposed macro element method in addition to the mass permeability method proposed by Asaoka et al. as the most common and conventional one. As an actual example of an embankment construction site, this research is of interest to the Mukasa area on the Maizuru-Wakasa expressway (construction started in 2005; road put into service in 2014), in which a thick soft ground containing clay and peat is underlying the embankment. In this case, test embankment constructed in 2006 with ground improvement by Sand drain method and an embankment located approximately 300m from the test embankment constructed in 2012 with vacuum consolidation are focused upon. . Using of various data from the study field such as laboratory test results, site investigations, and field observations, this study aims to: (1) describe the mechanical behavior of high compressive peat within the same theoretical framework as all other soil components from clay to sand, (2) validate the ability of the analysis methods used in this study to accurately simulate actual observed behaviors, (3) propose the effective countermeasures for the target area based on the prediction of future settlement and (4) discuss the improved effects of vertical drains/vacuum consolidation on soft ground including highly compressible peat in ensuring stability and reducing residual settlement.

This dissertation is started with a literature review that has researched about peat or highly organic content deposits. This work gives an overview of generation process, global distribution, classification for engineering purposes, typical engineering properties, and geotechnical problems involved with construction on ground containing peat. After that, this study focuses on the mechanical behavior of highly compressible peat in the Mukasa area. The results of triaxial and one-dimensional compression tests on undisturbed samples are reproduced by the model responses of the elasto-plastic constitutive equation SYS Cam-clay model to describe the characteristics of highly compressive peat based on the soil skeleton structure concept. In addition, the environmental sedimentation and the in-situ conditions are deduced based on the site investigations. It is found that, under the test embankment in the Mukasa area, as a result of deposition under continuous artesian conditions of the valley bottom created by fault movement, the peat has an extremely low consolidation yield stress and was in a state in which even a slight increase in stress would result in large-scale compression. In the following, this study confirms the ability of the soil-water coupled finite deformation analysis code ***GEOASIA*** itself, to simulate the large-scale deformation of an ultra-soft ground containing approximately 50-m-deep soft peaty soil layers under the test embankment of the Mukasa area. In this location, large-scale settlement in excess of 11 m occurred in approximately 3 years following embankment construction. While construction of the test embankment did not induce catastrophic slip failure, it dramatically impacted the surrounding ground. Field observations show that this large residual settlement was attributable to the delayed compression of the deep peaty soil layers, which were assumed at the design stage, not to be subject to settlement. The large-scale deformation of the ground observed in the approximately 4-year period starting with test embankment construction is simulated. For simplicity, in this calculation, the mass-permeability method is used as a macroscopic method to describe the improvement effect of sand drains. After confirming the ability of the soil-water coupled finite deformation analysis code ***GEOASIA***, the code is used to predict future settlement allowing continuous simulations without changing the parameters. These predictions are then used to evaluate the effectiveness of the countermeasures aimed not only at improving stability during construction, but also at reducing residual settlement. The results of these analyses were applied in the planning of large-scale repair work performed on the test embankment. And, when an embankment was subsequently constructed near the test embankment on the ground including a similar type of highly compressible peaty soil, ground improvement was conducted prior to embankment construction as a countermeasure against residual settlement. In this study, valuable field data related to these latter construction efforts is also presented.

Additionally, representing vertical drains in a numerical model using soil-water coupled finite element analysis, is a challenge when simulating particularly, vertical drain combined vacuum consolidation; the study proposes a new macro element method. The original macro element method proposed by Sekiguchi et al. can allow very accurate incorporation of the water absorption function of drains even under 2-dimnensional plane strain conditions. In this study the discharge function of vertical drains is newly added to the method by treating the water pressure in the drain as an unknown and adding a continuity equation for the drains to the governing equations. By this extension, the well-resistance phenomenon could be exhibited automatically depending on the analytical conditions. Numerical analyses are conducted after incorporating the new proposed macro element method into the analysis code ***GEOASIA***. The calculation results show that the proposed method enables highly accurate approximation in problems involving material and/or geometrical nonlinearity and multilayered ground. In addition, it is revealed that the proposed macro element method is capable of reproducing various phenomena occurring when the vacuum consolidation method is applied to clayey ground containing a middle sand layer. In the location of the middle sand layer waterproof sealing material is often wrapped to the surface of drains, in order to avoid propagation of vacuum pressure. The effects of such countermeasures can be also appropriately reproduced by the proposed method here.

Finally, by utilizing this newly proposed macro element method, simulation and investigation of the effects of ground improvement by vertical drains/vacuum consolidation on peaty ground are conducted. This dissertation focuses on the peaty ground that was improved by combination of vertical drain and vacuum consolidation under an embankment located approximately 300 m from the test embankment in the Mukasa area. The settlement value is quite smaller even at the same height of the test embankment; moreover, the settlement occurred widely on neighboring areas instead of upheaval. The results indicate that the new proposed macro element method incorporating into FEM geo-analysis program *GEOASIA* is capable of comprehensively and closely simulating not only the magnitude of settlement but also various ground behaviors including deformation of the surrounding ground and pore water pressure distributions. Furthermore, additional simulations are conducted by using the same analysis method and parameters to demonstrate that the settlement on surrounding areas is due to the propagation of vacuum pressure through middle sand layers. An advantage of the proposed macro-element method is that the mesh width does not have to be matched to drain spacing. In other words, it is possible to evaluate the effect of drain spacing using the same mesh. Therefore, this study conducts further calculations to evaluate the improvement effects of vertical drains/vacuum consolidation particularly focusing on various drain spacing. Here an ultra-soft ground with alternating peat and clay layers is modeled to present the typical ground where vacuum consolidation would be applied. In addition, the construction costs are estimated based on the actual construction costs in the Mukasa area in order to consider economic aspect. The analysis results pointed out that, although the use of vacuum consolidation in combination with vertical drains is effective in cases where it is necessary to limit deformation of the surrounding ground, the same reduction in residual settlement can be achieved using vertical drains alone, provided that drains are deployed at a sufficient frequency. When applying vertical drains/vacuum consolidation on a soft ground, it is important to carefully consider not only the ground conditions (ground permeability, the presence of a middle sand layer, etc.) but also the impact on, for instance; the ground adjacent to the improved area, construction costs, and construction time. The macro-element method newly proposed in this study could quantitatively simulate/evaluate the effects of various factors and should prove to be an effective tool for making comprehensive decisions in actual practice.