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Study on the pore water pressure dissipation method as a liquefaction countermeasure using soil–water coupled finite deformation analysis equipped with a macro-element method

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Abstract

A numerical simulation of the pore water pressure dissipation method was performed using the ***GEOASIA*** soil–water coupled finite deformation analysis code, which is capable of accounting for inertial forces, together with the elasto-plastic constitutive SYS Cam-clay model based on the soil skeleton structure concept, with the goal of quantitatively assessing the effects of this method as a countermeasure to liquefaction. At the same time, an effort was made to improve/enhance the calculation efficiency of the ***GEOASIA*** analysis code by incorporating a macro-element method, which up to this point has only been applied to consolidation problems. The main findings of this study are as follows: (1) the macro-element method is capable of yielding highly accurate approximations even for dynamic problems, (2) the method is capable of reproducing the suppression effect of the increase in pore water pressure associated with the pore water pressure dissipation method, even when a relatively coarse mesh is used, (3) the method is capable of reproducing the suppression effect of the decrease in effective stress due to the pore water pressure dissipation method, along with the resulting reduction in shear stiffness, lateral ground movement, and settlement and (4) it is possible to efficiently design the pore water pressure dissipation method with this method by first performing calculations using a 1-D mesh to determine the effective drain spacing prior to performing calculations using 2-D or 3-D meshes.

Keywords: Pore water pressure dissipation method; Liquefaction countermeasure; Soil–water coupled analysis; Macro-element method

1. Introduction

In the pore water pressure dissipation method, liquefaction during earthquakes is inhibited by suppressing the increase in pore water pressure by means of the installation of vertical drains. The trade-off for this method is that some degree of ground surface settlement due to compaction must be allowed for. Accordingly, in addition to the question of whether or not the method can be used to prevent liquefaction, it is important to be able to predict the degree of deformation that will occur as a result of ground compaction. The primary objective of this study is to employ a soil–water coupled analysis to quantitatively predict the effects, including the degree of ground deformation, of the pore water pressure dissipation method as a countermeasure to liquefaction.

A survey of the existing literature on the pore water pressure dissipation method reveals that, while there are some examples of model-based experimental approaches (e.g., Tanaka et al.,

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1984; Unno et al., 2012), there has been essentially no research involving a full-scale numerical analysis of the real ground. This is because there are three major challenges impeding the numerical simulation of the pore water pressure dissipation method. The first and second challenges are closely related to the principle underlying the method. Countermeasures to liquefaction that employ cement treatment or chemical grouting seek to harden the liquefaction-prone layer, and do in fact prevent liquefaction of at least the target layer. Densification methods, exemplified by the sand compaction pile (SCP) method, also increase the liquefaction strength and liquefaction resistance of the treated layer. Meanwhile, as is well known, the pore water dissipation method seeks to prevent liquefaction by suppressing the increase in pore water pressure and does not attempt to improve the mechanical properties or conditions (i.e., to proactively increase the strength or rigidity) of the ground in question. In other words, it is a countermeasure method with the potential for actually causing liquefaction. Thus, simulations must also be able to reproduce liquefaction in cases where the countermeasure does not perform as expected. As mentioned earlier, because it is a method that, when effective, causes compaction, the constitutive equation must be capable of reproducing both compaction and liquefaction in response to external forces. In order to reproduce liquefaction or compaction behavior that is likely to occur during an earthquake, in addition to the settlement due to consolidation, which is especially problematic after liquefaction, the underlying mechanical theory and the numerical analysis method, employed to solve the governing equation, must be able to seamlessly handle deformation and failure behavior during and after an earthquake and to reproduce the effect of partial drainage. Given these requirements, in this research, we employed the SYS Cam-clay elasto-plastic constitutive model based on the soil skeleton structure concept (Asaoka et al., 2002) installed in the ***GEOASIA*** soil–water coupled finite deformation analysis code (Noda et al., 2008). The SYS Cam-clay model is equally capable of handling liquefaction and compaction as phenomena resulting from the degradation of the structure and the accumulation of overconsolidation, while also accounting for the mechanical behavior of a wide range of ground materials. ***GEOASIA*** is a soil–water coupled finite element analysis code based on the two-phase mixture theory in the finite deformation regime, and partial drainage effects appear naturally in the analysis results. It integrates the rate-type equation of motion over time, based on an extended Wilson-θ method adopted for the equation. As such, it is capable of consistently handling a wide range of ground deformation and failure behavior (before, during, and after an earthquake) without having to distinguish between quasi-static and dynamic problems.

The third challenge facing the numerical simulation of the pore water pressure dissipation method concerns the difficulty of representing a large number of vertical drains installed in the ground. While the ideal solution would be to represent such drains by increasing the mesh density, this would require a very large number of elements and would not be practical when performing a 3-D analysis. In other words, to be able to perform a practical simulation of the pore water pressure dissipation method using a numerical analysis code that meets the first two requirements, what is needed is the incorporation of some means of efficiently representing the water absorption and discharge functions of vertical drains. The macro-element method (Sekiguchi et al., 1986; Yamada et al., 2015), which is a type of homogenization method, is frequently employed in effective stress analyzes for consolidation-related problems, which suffer from the same difficulties as those involved in representing vertical drains. In the present study, we attempted to resolve this issue by applying the macro-element method to a dynamic problem, when it had only been applied, up to this point, to quasi-static problems. The method was recently extended by the authors to include the discharge function of vertical drains in addition to the water absorption function that the original macro-element method has (Yamada et al., 2015). In this paper, we attempted to incorporate the macro-element method into the ***GEOASIA*** soil-water finite deformation analysis code, which is capable of accounting for inertial forces.

In the following sections, we first describe how the macro-element method was introduced to the soil–water finite deformation analysis code with inertia terms. Next, we demonstrate that the macro-element method is capable of generating highly accurate approximations for dynamic problems, using the example of a 3-D unit cell model surrounding a single drain. Furthermore, in order to confirm the effect of suppressing the increase in pore water pressure on reducing deformation, such as lateral flow, we provide an example of numerical calculations conducted for the case of sandy soil directly beneath an embankment, to which the pore water pressure dissipation method is applied as a countermeasure to liquefaction. In addition, with countermeasure design in mind, we briefly discuss approaches for reducing the number of test calculations required for determining the drain spacing and improvement region.

2. Application of macro-element method to soil–water finite deformation analysis code with inertia terms

The soil–water finite deformation analysis with inertia terms, developed by the authors Noda et al., 2008), employs a so-called $\boldsymbol{u}$-p formulation to obtain the nodal displacement velocity vector $\{\boldsymbol{v}^N\}$ and representative pore water value u for each element by solving the space-discretized rate-type equation of motion and soil–water coupled equation given by:

$$\mathrm{M}\{\ddot{\boldsymbol{v}}^N\} + \mathrm{K}\{\boldsymbol{v}^N\} - \mathrm{L}^{\mathrm{T}}\dot{u} = \{\dot{\boldsymbol{f}}\} \tag{1}$$

$$\frac{k}{g}\mathrm{L}\{\dot{\boldsymbol{v}}^N\} - \mathrm{L}\{\boldsymbol{v}^N\} = \sum_{i=1}^{m} \alpha_i (h - h_i)\rho_w g \tag{2}$$

where M is the mass matrix, K is the tangent stiffness matrix, L is the matrix for converting $\{\boldsymbol{v}^N\}$ to the element volume change rate, $\{\dot{\boldsymbol{f}}\}$ is the nodal force rate vector, $\{\dot{\boldsymbol{v}}^N\}$ and $\{\ddot{\boldsymbol{v}}^N\}$ denote the nodal acceleration and jerk vectors, h and h_i.