Soils and Foundations 2015;55(5):1113–1128

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Soils and Foundations

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SOILS AND FOUNDATIONS

Macro-element method with water absorption and discharge functions for vertical drains

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Received 30 July 2014; received in revised form 13 March 2015; accepted 13 May 2015

Abstract

When simulating the vertical drain method using a soil–water coupled finite element analysis, a macro-element method can be used as a means of approximately applying the water absorption function of drains to individual elements. In this paper, the discharge function of vertical drains was 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 extending the method in this way, the analytical results came to exhibit the well-resistance phenomenon automatically, depending on the analytical conditions. Numerical analyses were conducted after incorporating the proposed macro-element method into a quasi-static soil–water coupled elasto-plastic finite element method based on the finite deformation theory. The main conclusions are as follows: (1) the proposed method enables highly accurate approximations for problems involving material and/or geometrical nonlinearity and multilayered grounds; (2) the proposed macro-element method is capable of reproducing various phenomena that occur when the vacuum consolidation method is applied to a clayey ground containing a middle sand layer; (3) by following the formulation used in this paper, it is unnecessary to match the mesh division width to the drain arrangement and spacing. In addition, it is possible to obtain solutions that are minimally affected by the mesh size.

Keywords: Macro-element method; Vertical drain method; Vacuum consolidation method; Well resistance; Soil–water coupled analysis; Finite element method; Finite deformation theory; Elasto-plasticity; Multilayered ground

1. Introduction

It is well known that the soil–water coupled elasto-plastic finite element analysis is one of the most important tools for analyzing problems involving ground deformation and failure. It goes without saying that a challenge faced when simulating the vertical drain (VD) method, using this numerical analysis approach, is how to represent the VDs in the numerical model. The simplest method is to model the VDs with finite elements after dividing the mesh finely in the improved region (e.g., Borges, 2004). While this is an ideal approach, from the standpoint of being able to precisely calculate stress, strain, and water flow, it is problematic in that it requires a 3-dimensional analysis and a simultaneous evaluation of a vastly increased number of elements. The corresponding approach for analysis under 2-dimensional plane strain conditions is to distribute thin, highly permeable elements vertically or permeable boundaries in the ground. In this case, as wall-like drains are created, special manipulation of some type is required to match the progress of consolidation between the 3-dimensional condition and the 2-dimensional plane strain

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Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2015.09.012
0038-0806/

condition (e.g., Shinsha et al., 1982; Hird et al., 1992; Indraratna et al., 2004). There is a technique, the mass-permeability concept, that does not require increasing the mesh density by assigning the macroscopic permeability to the improved ground in order to consider the acceleration effect of consolidation resulting from the VD method. While this offers a simple way of presenting the problem, it still requires a means of deciding the mass-permeability of a ground with drains. Aasoka et al. (1995) proposed a back-analysis method for determining the mass-permeability of a ground with drains. Chai et al. (2001) reported a method for calculating the vertical macroscopic coefficient of permeability of the ground based on the drain diameter and drain arrangement. However, the problem with these methods is that, even though they are able to simulate the settlement behavior of the ground surface, they do not necessarily accurately reproduce the consolidation process in the ground. Sekiguchi et al. (1986) proposed a different approach to simulating the VD method with the goal of reducing computational costs. Specifically, they attempted to express the accelerated consolidation associated with the VD method by assigning the water absorption function of drains to each element in the drain-improved region. This can be considered as a type of homogenization method that enables the reproduction of accelerated consolidation effects due to drains at the macroscopic level without dealing with the heterogeneity that occurs around individual drains. Sekiguchi et al. (1986) used the term "macro-element method" to refer to this approach. It is a useful method that allows for the very accurate incorporation of the water absorption function of drains even under 2-dimensional plane strain conditions. Sekiguchi et al. (1986) validated their proposed method through experiments conducted on a test embankment under which the soft ground was improved by the installation of sand drains. Based on this approach, Aasoka et al. (1995) proposed the aforementioned method for determining the mass-permeability of a drain-improved ground. Takeyama et al. (2008) and Arai et al. (2008) performed simulations of vacuum consolidation using the same method. Hirata et al. (2010) included the well resistance coefficient proposed by Yoshikuni and Nakanodo (1974) and/or Yoshikuni (1979) into the macro-element to simply account for the consolidation delay resulting from the well resistance. Also, Chai et al. (2013) discussed several methods for incorporating the VD effects into the soil–water coupled finite element method including the original macro-element method.

One of main objectives in this paper is to newly extend the function of the original macro-element method. Specifically, it is proposed that the water pressure in the drain, which has been specified as an analytical condition in previous versions of the method, be treated as an unknown. In the proposed method, a continuity equation for drains is added to the governing equations in order to compensate for the increased unknowns. In previous versions of the macro-element method, as a consequence of approximating the drain permeability as infinity, the pore water absorbed into drains would simply vanish. In the proposed method, however, this pore water is transported to the ground surface through drains with finite permeability. That is to say, the proposed macro-element method newly obtains a discharge function for the drain while retaining the water absorption function included in previous versions. Analysis showed that, in simulations with this rational expansion, a well resistance spontaneously occurs under certain conditions. Furthermore, in previous versions of the macro-element method, it was necessary to match the mesh division width to the drain spacing or an integral multiple thereof. If this restriction was removed, it would be possible to use the same mesh to investigate the effect of the drain spacing. In this paper, a formulation is conducted whereby the solution is not constrained by the mesh division width.

The structure and the objective of the present paper are as follows. First, the new macro-element method that incorporates water absorption and discharge functions for VDs is formulated. Next, using a soil–water coupled elasto-plastic finite element analysis code, based on the finite deformation theory incorporating the above formulation, the calculation results for an axisymmetric unit cell model surrounding a single drain are shown to ascertain the baseline performance and approximation accuracy. Finally, a series of simulation results for the vacuum consolidation of a ground containing a middle sand layer are shown to demonstrate the advantage of treating the water pressure in the drain as an unknown. In addition, mesh sensitivity is also verified for the same analytical target.

2. Formulation of new macro-element method equipped with water absorption and discharge functions for vertical drains

2.1. Soil–water coupled elasto-plastic finite element governing equations and macro-element method

Asaoka et al. (1994, 1997b) proposed a quasi-static soil–water coupled elasto-plastic finite element method based on finite deformation as an extension of the method of Akai and Tamura (1978), which is of the type proposed by Christian and Boehmer (1970). Extending this approach by the introduction of macro-elements is considered herein.

The governing equations for the above numerical analysis methods are represented as follows:

$$\mathrm{K}\left\{ \boldsymbol{v}^N \right\} - \mathrm{L}^{\mathrm{T}}\dot{u} = \left\{ \dot{\boldsymbol{f}} \right\} \tag{1}$$

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

Eqs. (1) and (2) represent a spatially discretized rate-type equilibrium equation and a soil–water coupled equation, respectively. By solving these equations simultaneously, the node velocities $\{\boldsymbol{v}^N\}$ and the representative value for pore water pressure u at each element are obtained. Here, K represents the tangent stiffness matrix, L is the matrix for converting $\{\boldsymbol{v}^N\}$ to the elemental volume change rate, $\{\dot{\boldsymbol{f}}\}$ is the nodal force rate vector, h and h_i represent the total head corresponding to the water pressure for the element in question