Available online at www.sciencedirect.com
ScienceDirect
Soils and Foundations 57 (2017) 472–487
www.elsevier.com/locate/sandf

Verification of a macro-element method in the numerical simulation of the pore water pressure dissipation method – A case study on a liquefaction countermeasure with vertical drains under an embankment

Toshihiro Nonaka [a,*], Shotaro Yamada [b], Toshihiro Noda [a]

[a] Disaster Mitigation Research Center, Nagoya University, Nagoya, Japan
[b] Department of Civil Engineering, Nagoya University, Nagoya, Japan

Received 22 May 2016; received in revised form 28 December 2016; accepted 21 January 2017
Available online 30 May 2017

Abstract

In the simulation of the vertical drain method using a soil-water coupled finite element analysis, a macro-element method has often been used as an approximate method to introduce the water absorption functions of drains into individual elements. In order to extend the function of this method, the authors modified the formula of the flow coefficient from soil to drains and introduced the discharge function of vertical drains to the method by treating the water pressure in the drains as an unknown and adding a continuity equation for the drains to the governing equations. The first attempt made it possible to divide a finite element mesh independently of the drain arrangement and the drain spacing, and the second attempt enabled the well resistance to be automatically generated by a series of calculations depending on the given conditions. Furthermore, although the macro-element method has been applied to quasi-static problems in most cases, the authors applied the expanded one to dynamic problems by equipping it with the soil-water coupled finite deformation analysis code ***GEOASIA*** with the inertial term. In this paper, in order to verify the new macro-element method in a dynamic problem, the results of a 2D approximate model using the new macro-element method were compared with those of a 3D exact model where vertical drains were exactly represented by finely dividing the finite element mesh in the case of a sand ground improved by the pore water pressure dissipation method under the embankment. The findings of this study are as follows: (1) 2D mesh-based analyses under plane strain conditions, using the new macro-element method, can accurately approximate 3D mesh-based analyses with a fine mesh in dynamic problems in terms of changes in the excess pore water pressure and ground deformation; (2) the new macro-element method can adequately evaluate the influence of drain spacing on a countermeasure for liquefaction in the quantitative sense, while using a single mesh; and (3) the new macro-element method improves the calculation efficiency in the simulation of the pore water pressure dissipation method by laborsaving in mesh-dividing and dramatically reducing the calculation time.

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

1. Introduction

In Japan, there have been significant concerns about the liquefaction damage caused by great earthquakes, particularly in the Tokyo Bay area after the 2011 Great East Japan Earthquake (Yasuda et al., 2012). The pore water

Peer review under responsibility of The Japanese Geotechnical Society.
* Corresponding author.
E-mail addresses: nonaka@nagoya-u.jp, nonakatoshihiro1009@gmail.com (T. Nonaka).

http://dx.doi.org/10.1016/j.sandf.2017.05.012

pressure dissipation method (PWPDM) attracts a lot of attention because it is relatively inexpensive and superior in feasibility. However, the construction of a countermeasure to liquefaction with PWPDM has been hampered by the lack of an effective analytical method for it.

The authors (Yamada et al., 2015) extended the functions of the macro-element, which is one of the homogenization methods proposed by Sekiguchi et al. (1986), and designed a numerical-analysis technique that quantitatively evaluates the improvement effect of PWPDM by applying it to dynamic problems (Noda et al., 2015). The primary objective of this study is to verify this new method for dynamic problems with PWPDM.

One of the issues with the numerical analysis of PWPDM is the enormous calculation cost because a 3D analysis with a fine mesh is required to represent a large number of vertical drains installed in the ground. The authors have focused on the macro-element method as a means to resolve this issue. Since the macro-element method introduces the water absorption and discharge functions of drains into the individual elements under 2D plane strain conditions without using a fine mesh, it is possible to dramatically improve the calculation efficiency. Sekiguchi et al. (1986) attempted to express the accelerated consolidation associated with the vertical drain method by applying the macro-element method. Moreover, they validated their proposed method through observations conducted on a test embankment under which the soft ground was improved by the installation of sand drains. Although this method had previously been applied only to quasi-static problems, the authors applied it to a dynamic problem by equipping it with the soil-water coupled analysis code ***GEOASIA*** (Noda et al., 2008) with the inertial term (Noda et al., 2015). The noteworthy features of the macro-element method proposed by the authors were that the division of the finite element mesh could be specified independently of the drain arrangement and the drain spacing and that well resistance was automatically generated by a series of calculations depending on the given conditions.

In PWPDM, liquefaction can be inhibited during an earthquake by suppressing the increase in pore water pressure by means of the installation of vertical drains. Instead of this, some degree of ground surface settlement due to compaction must be allowed. 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. This is the other issue related to the numerical analysis of PWPDM. ***GEOASIA*** is capable of uniformly handling the following phenomena: (1) both compaction and liquefaction and (2) both the settlement due to compaction during an earthquake and the consolidation settlement after liquefaction. Therefore, the code can overcome these issues at the same time.

In the previous numerical-analysis approaches to PWPDM, drains were expressed as permeable boundaries (e.g., Tashiro et al., 2015) or by increasing the permeability coefficient of the finite element (e.g., Papadimitriou et al., 2007). However, these methods require a fine mesh and an enormous calculation cost. On the contrary, homogenization methods enable the avoidance of using a fine mesh. Poulos (1993), Omine and Ohno (1997), Omine et al. (1999) and Ng and Tan (2015) considered homogenization methods for ground improvement with the columnar improvement method. Although quasi-static problems were targeted in these studies, verifications of these methods were conducted. Sato et al. (2005) and Ueda and Murono (2015), among others, investigated homogenization methods for dynamic problems. Their studies of dynamic problems did not match the progress of the quasi-static studies because the accuracy of one analysis was not verified, and the other was only a basic investigation employing a linear analysis. Additionally, their studies only targeted SCP (the sand compaction pile method); PWPDM was not targeted.

Oka et al. (1992) and Kato et al. (1994) applied the macro-element method in a numerical analysis of PWPDM. They introduced the original macro-element method proposed by Sekiguchi et al. (1986) into LIQCA (the development group of liquefaction analysis code LIQCA, 2004) and examined the suppression of the increase in excess pore water pressure (EPWP). However, the accuracy of this approximation has never been verified.

As previously mentioned, the authors have conducted numerical simulations of PWPDM using the macro-element method with a function extension (Noda et al., 2015). That study showed that this method could provide accurate approximations in the simulation of a single drain and in the region of the ground where this drain was effective. Nevertheless, it remains to be shown whether or not this method provides accurate approximations in the case of simulations targeting large scale and highly heterogeneous problems where multiple drains and soil structures need to be treated. Moreover, in the previous study, only a single verification was conducted for the case in which the produced improvement effect was great. Therefore, more comprehensive verifications are required so that the macro-element method can earn higher credibility.

In this paper, the new macro-element method, extended by the authors and introduced to the soil-water coupled analysis code ***GEOASIA***, was verified in a dynamic problem. The case of a sand ground improved by PWPDM under an embankment was taken as an example. Specifically, the results of a 2D mesh-based analysis under plane strain conditions, using the new macro-element method, were compared to those of a 3D mesh-based analysis in which vertical drains were exactly represented by finely dividing the finite element mesh. Some analyses were conducted where the drain spacing was changed, and the cases for which a great improvement was produced as well as the cases for which it was scarcely produced are discussed. And, as previously mentioned, the division of the finite element mesh could be specified independently of the drain