Numerical simulation of pore water pressure dissipation method based on a soil-water coupled analysis enhanced by macro element method

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ABSTRACT

In the excess pore water pressure dissipation method (referred to as EPWPD method hereafter), ground settlement occurs to some extent due to compaction, because vertical drains in the ground could prevent the pore water pressure from rising during earthquake. Therefore, in this method, it is particularly important to predict the amount of ground deformation under liquefaction as well as to discuss whether liquefaction could be prevented. In this study, the fundamental characteristics of this method were examined by a series of numerical simulations to quantitatively predict the ground deformations. The macro element method, which had been applied only to consolidation phenomena, was mounted on a soil-water coupled finite deformation analysis code GEOASIA which is capable of handling inertial forces and utilizes the SYS Cam-clay as the elasto-plastic constitutive model of the soil skeleton. The main conclusions obtained in this study are outlined next. 1) It was evident that the macro element method that had been only used for quasi-static problems has satisfactory approximation accuracy even in dynamic problems. 2) Basic characteristics of EPWPD method (i.e., liquefaction/compaction during earthquake and consolidation settlement after earthquake) can be adequately reproduced even when a comparatively rough finite element mesh without accounting the drains pitch is used in the macro element method mounted on the analysis code GEOASIA. 3) It is possible to efficiently design the effective drain spacing under the EPWPD method by conducting 1-dimensional mesh analysis prior to multi-dimensional mesh analysis.

Keywords: pore water pressure dissipation method, liquefaction countermeasure, soil-water coupled analysis, macro element method

1 INTRODUCTION

In the excess pore water pressure dissipation method (referred to as EPWPD method hereafter), ground settlement occurs to some extent due to compaction, because vertical drains in the ground could prevent the pore water pressure from rising during earthquake. Therefore, in this method, it is particularly important to predict the amount of ground deformation under liquefaction as well as to discuss whether liquefaction could be prevented. In this study, the fundamental characteristics of this method were examined by a series of numerical simulations to quantitatively predict the ground deformations. The macro element method, which had been applied only to consolidation phenomena, was mounted on a soil-water coupled finite deformation analysis code GEOASIA (Asaoka and Noda, 2007, Noda et al., 2008) which is capable of handling inertial forces and utilizes the SYS Cam-clay model (Asaoka et al., 2002) as the elasto-plastic constitutive model of the soil skeleton. The reason that was calculated using GEOASIA is that this code can handle uniformly liquefaction/compaction during earthquake and consolidation settlement after earthquake that are necessary in numerical simulation of the pore water pressure dissipation method. Another important thing in numerical simulation of the EPWPD method is how to improve efficiency of calculation. It takes a huge calculation cost, in the case that meshes of a large number of vertical drains installed in the ground and the ground around drains are finely divided. The macro element method (Sekiguchi et al., 1986, Yamada et al., 2014), which is a type of homogenization method, is frequently employed in effective stress analyses for consolidation-related problems, which suffer from the same difficulties in representing vertical drains. In the present study, we attempted to resolve this issue by applying the macro element method, which up to this point had only been applied to quasi-static problems, to a dynamic problem. The method was recently extended by the authors to treats water pressure in the drain as an unknown (Yamada et al., 2014). 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 (Noda et al. 2014; Tashiro and Nguyen, 2015).

In the sections below, we first verify the accuracy of approximations using the macro element method. Next, we provide an example of numerical calculations conducted for the case of sandy soil directly beneath an embankment, to which the EPWPD method is applied as a liquefaction countermeasure. In addition, we briefly discuss approaches for reducing the number of test calculations required for determining the drain spacing and improvement region.

2 ACCURACY OF APPROXIMATIONS USING THE MACRO ELEMENT METHOD FOR DYNAMIC PROBLEMS

2.1 Analysis conditions

The analysis was conducted for a 3-D unit cell model surrounding a single drain. The ground to be improved was 10 m thick, loose sandy ground. Two models were constructed: an 'exact model' in which the analytical domain was a mesh that was finely divided even in the horizontal direction, and an 'approximate model' utilizing the macro element method, for which the mesh was not divided horizontally. The finite element meshes and boundary conditions adopted in the two models are presented in Fig. 1, respectively. We assumed drains arranged in a square pattern in horizontally layered ground at a spacing of 1.0 m and applied a periodic boundary to the sides of the analysis domain. A viscous boundary was applied to the bottom boundary in the horizontal direction while a fixed boundary condition was applied in the vertical direction. In terms of hydraulic boundary conditions, an impermeable condition was applied to both the side and bottom boundaries. The boundary at the ground surface was initially assigned a water pressure of zero, and later a permeable condition was applied that retained a prescribed head (i.e., the case in which there is standing water). For the vertical drain, we assumed a spiral drain (A society for the study of DEPP Method, 2011) with a diameter of 0.1 m and a permeability coefficient of 7.0×10⁻⁸ cm/s. In the exact model, the drain part was represented as a cavity, and the part adjacent to the drain, was set to be a permeable boundary with a constant head, similar to the ground surface. The material constants and initial values adopted for the ground and embankment are presented in Table 1. The material constants for the viscous boundary at the bottom of the model and the drain are shown in Tables 2 and 3, respectively. The ground was assumed to be a loose sandy soil that would be prone to liquefaction if not improved. The input ground motion is a seismic wave of the kind associated with a Tokai-Tonankai-Nankai linked-type earthquake having a main shock duration of 120 s and a maximum acceleration on the order of 180 gal. Excitation occurs in two horizontal directions.

![Fig. 1. Finite element mesh and boundary conditions](image)

**Table 1. Material constants and initial values for the ground and embankment**

| Parameter | Ground | Embankment |
|-----------|--------|------------|
| Critical state index M | 1.00 | 1.35 |
| NCL intercept N | 1.98 | 1.71 |
| Compression index K | 0.050 | 0.110 |
| Swelling index k | 0.016 | 0.020 |
| Poisson’s ratio ν | 0.3 | 0.3 |

**Table 2. Material parameters of viscous boundary**

| Parameter | Value |
|-----------|-------|
| Bedrock density ρ (g/cm³) | 2.00 |
| S-wave velocity in the bedrock Vₜ (m/sec) | 150.0 |

**Table 3. Material parameters of macro element method**

| Parameter | Value |
|-----------|-------|
| Equivalent diameter d (m) | 1.13 |
| Diameter of circular drain d (m) | 0.18 |
| Permeability coefficient of circular drain kₜ (cm/sec) | 7.00×10⁻⁹ |

2.2 Analysis results

The excess pore water pressure distribution for each model is shown in Fig. 2. The figure also shows the distribution of the vertical cross section including the
drain for the exact model. Both the exact and approximate models yielded similar trends for the distributions at the ground surface. In addition, the water pressure appears to be lower in the vicinity of the drain in the exact model. Figure 3 shows the time-excess pore water pressure ratio relationship. The upper surface representing the exact model shows values for elements at point that is 0.4 meters away from drain. Following the change in excess pore water pressure ratio over time, it can be seen that, for these element locations, the approximate model yields essentially the same values for the pressure ratio as the exact model does. Furthermore, in both models, although the excess pore water pressure ratio continues to rise for a period of time after the onset of shaking, it stops rising after reaching a value of 0.8 or so, and therefore does not reach the liquefaction. (Calculations for the same ground without countermeasures resulted in an excess pore water pressure ratio greater than 0.95.)

From the above, it can be seen that the approximate model is capable of closely approximating the change in water pressure generated by the exact model, at least for the locations compared in Fig. 3. Next, we set out to determine whether or not the model could accurately approximate the ground response. Figures 4 show the change with time of the horizontal acceleration of the ground surface and the bottom of the ground. Essentially the same response was produced by the exact and approximate models.

**Fig. 4.** Acceleration response

Next, we compared the relationship between the mean effective stress and the specific volume in order to investigate the behavior of elements in the ground. The elements used in this comparison were located at a depth of 2.5 m. For the exact model, the element at the prescribed depth located at point that is 0.4 meters away from drain. As shown in Fig. 5, both elements exhibit very similar behavior.

**Fig. 5.** Compaction behavior during earthquake

The mean effective stress falls, at the very most, to approximately 2/3 of the original value. On the other hand, compression due to compaction occurs during the earthquake. Furthermore, very little compression due to consolidation appears to occur after seismic activity.
ends. Thus, the suppression of the increase in pore water pressure attributable to the water absorption function of the vertical drains, and the ground compaction that occurs in its place can be reproduced by the numerical calculations. As mentioned above, the macro element method is highly effective at approximating the water absorption and discharge functions of vertical drains. Meanwhile, we need to recognize that it is the SYS Cam-clay model and the GEOASIA code that allows us to reproduce the compaction behavior and the dynamic calculation.

3 A CALCULATION EXAMPLE OF IMPROVEMENT EFFECT FOR THE EXCESS PORE WATER PRESSURE DISSIPATION METHOD

3.1 Analysis conditions

Next, in order to confirm the effect of suppressing the pore water pressure increase on inhibiting ground deformation such as lateral flow, we describe calculations for the case where liquefaction countermeasures based on the EPWPD method are applied to sandy ground directly beneath an embankment. The finite element mesh and the boundary conditions adopted are shown in Fig. 6.

An embankment with a final height of 6m was added to the horizontally layered ground over a period of 18 days, and the consolidation was calculated until a steady state was achieved. Next, the EW component of the ground motion used in the calculations in the previous section was applied to this embankment-ground system, and consolidation was allowed to proceed until the excess pore water pressure was completely dissipated. (Both the quasi-static and dynamic processes in the period from before the earthquake started to after it finished were consistently calculated by using a single analysis code.) The ground directly under the embankment was designated as the improved region, and the macro element method was applied to its relevant parts. In addition, a high-permeability drainage mat was assumed to be laid between the embankment and the ground, and a permeable boundary (atmospheric pressure) was assigned to the embankment-ground interface. The values shown in Tables 1 to 3 were adopted as material constants and initial values for the ground, and material constants for the viscous boundary and macro element.

3.2 Analysis results

Figure 7 shows the pore water pressure distribution immediately following the cessation of ground motion for cases of unimproved ground and ground with a drain spacing of 0.8 m. In order to make the deformation easier to see, a thick line has been drawn in the figures demarking the sides of the improvement region and the embankment perimeter prior to the earthquake. Using the macro element method, the effect of the EPWPD method on suppressing the water pressure increase becomes readily apparent in the analysis results. Lateral flow and settlement of the ground directly beneath the embankment are clearly reduced, in addition to deformation of the embankment itself. When no countermeasures are applied, large-scale lateral flow of the ground occurs as a result of the reduction in shear modulus as the effective stress approaches the origin along with the increase in water pressure. In contrast, when the countermeasures are applied, the decrease in effective stress is halted, which in turn inhibits the reduction in the shear modulus of the ground, thereby decreasing the lateral flow and accompanying settlement.

Figure 8 shows the dependence of the rates of water pressure increase, settlement, and lateral flow, as defined below, on the drain spacing.

\[ \text{[Water pressure increase rate]} = \frac{\text{[maximum pore water pressure with ground improvement]}}{\text{[maximum pore water pressure]}} \]
water pressure without ground improvement]
\[ \text{Settlement rate} = \frac{\text{final settlement at the embankment crown center with ground improvement}}{\text{final settlement at the embankment crown center without ground improvement}} \]
\[ \text{Lateral flow rate} = \frac{\text{final width of embankment bottom with ground improvement}}{\text{final width of embankment bottom without ground improvement}} \]

The settlement rate and the lateral flow rate include the amount of deformation due to consolidation processes that occur after the earthquake. By reducing the drain spacing, deformation such as settlement and lateral flow can be sufficiently suppressed due to inhibition of the increase in pore water pressure. For the analysis conditions in this study, the effect of the drain starts to appear at a spacing of approximately 2.0 m, and increases as the spacing falls below 1.0 m.

![Graph](image)

**Fig. 8. Relationship between drain spacing and improvement effects**

### 3.3 Proposal of an efficient design procedure on the improved effect using 1-D mesh-based analysis

As mentioned in the introduction, because the pore water pressure dissipation method allows for a certain degree of deformation, when determining drain spacing and improved region, the prediction of the amount of deformation is essential. The above results suggest that an effective stress analysis with improved calculation efficiency by introducing the macro element method is a promising approach to achieving this. At the same time, although the calculation efficiency is improved through application of the macro element method, it is still desirable to limit the number of test cases as much as possible. As can be seen in Fig. 8, because only a limited range of drain spacings are actually effective, it is possible to refine the number of cases calculated as long as the range of effective drain spacings is ascertained beforehand. The other important point illustrated in Fig. 8, which may be obvious from the underlying principle of this particular ground improvement method, is the strong correlation between the suppression of the pore water pressure increase and the inhibition of deformation. Although 2-D or 3-D mesh-based analyses are necessary for detailed prediction of deformation, an analysis using a 1-D mesh could possibly be sufficient for capturing the effects of suppression of the pore water pressure increase, assuming that this is the sole aim of the endeavor. Therefore, we investigated the relationship between the drain spacing and suppression of the pore water pressure increase via the 1-D mesh-based analysis shown in Fig. 9. The analysis conditions were as shown in the figure, and the material constants and initial values for the ground were the same as those used in the 2-D mesh-based analysis. However, for simplicity, in the 1-D mesh-based analysis, the presence of the embankment was accounted for by adding a distributed load to the ground surface. The 1-D mesh-based analysis results are shown together with the results of the 2-D mesh-based analysis in Fig. 10. It is evident that very similar relationships between the drain spacing and the suppression of the water pressure increase were obtained by the 1-D and 2-D mesh-based analyses. Thus, it can be concluded that the design process can be further streamlined by first performing a 1-D mesh-based analysis to determine the range of effective drain pitches, prior to performing 2-D or 3-D mesh-based analyses.

![Diagram](image)

**Fig. 9. Finite element mesh and boundary conditions (1-D mesh)**

![Diagram](image)

**Fig. 10. Relationship between drain spacing and suppression of water pressure increase (comparison of 1-D and 2-D mesh based analyses)**
4 CONCLUSIONS

The main conclusions obtained in this study are outlined below.

1) It was evident that the macro element method that had been only used for quasi-static problems has satisfactory approximation accuracy even in dynamic problems.

2) Basic characteristics of EPWPD method (i.e., liquefaction/compaction during earthquake and consolidation settlement after earthquake) can be adequately reproduced even when a comparatively rough finite element mesh without accounting the drains pitch is used in the macro element method mounted on the analysis code GEOASIA.

3) It is possible to efficiently design the effective drain spacing under the EPWPD method by conducting 1-dimentional mesh analysis prior to multi-dimensional mesh analysis.

In addition, although this did not arise in the calculations carried out in present study, because the macro element method proposed by the authors’ research group treats water pressure in the drain as an unknown, it is capable of treating cases of drainage stagnation and liquefaction that result from insufficient discharge capacity of the vertical drains. Furthermore, because the macro element method formulized by the authors does not require mesh division to be matched to the drain spacing, it is possible, as demonstrated in this study, to investigate the effect of different drain pitches using the same mesh. This is another notable advantage of using the macro element method.

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