Simulation and evaluation of improvement effects by vertical drains/vacuum consolidation on peat ground under embankment loading based on a macro-element method with water absorption and discharge functions

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Abstract

The authors previously extended the macro-element method proposed by Sekiguchi to include water absorption and discharge functions and incorporated this into a soil–water coupled finite deformation analysis code capable of accounting for inertial forces. The primary objective of this study is to validate the ability of the proposed method to simulate actual ground behavior by comparing the simulation results with the actual measurements of the embankment loading of a soft peat ground improved with vertical drains and vacuum consolidation. It was found that the proposed method is capable of comprehensively and closely simulating not only the magnitude of settlement, but also various ground behaviors, including the deformation of the surrounding ground and pore water pressure distributions. Furthermore, additional simulations were performed to elucidate the effect of a continuous middle sand layer found to exist and to span the entire improved area at an actual embankment site.

The next objective of this study is to investigate the impact of ground improvement, using vertical drains and vacuum consolidation with embankment loading on a soft ground, placing a particular focus on the effect of drain spacing. In this case, an ultra-soft ground with alternating peat and clay layers was modeled to represent a typical ground to which vacuum consolidation would be applied. Based on a series of simulations, it was found that, although the use of vacuum consolidation in combination with vertical drains is effective in cases where it is necessary to limit the deformation of the surrounding ground, the same reduction in residual settlement can be achieved using vertical drains alone, provided that the drains are deployed at a sufficient frequency.

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Keywords: Peat; Embankment loading; Vertical drain; Vacuum consolidation; Soil–water coupled analysis; Macro-element method

1. Introduction

When an embankment is constructed on a soft ground, slip failure during embankment loading or substantial residual settlement can occur after its entry into service. Such large-scale deformation can have a long-term and widespread impact on the surrounding ground.
To date, the authors have simulated the mechanical behavior of a wide range of soft soils, from naturally deposited clay to high water content peat, using the same theoretical framework as for other soil materials, such as sand and intermediate soil, namely, the elasto-plastic constitutive SYS Cam-clay model based on the soil skeleton structure concept (Asaoka et al., 2002). In addition, the authors have predicted and simulated the long-term settlement and have also identified the determinants of and proposed countermeasures to such phenomena as slip failure and residual settlement in relation to the construction of embankments on soft grounds using a soil–water coupled finite deformation analysis (Noda et al., 2005; Takane et al., 2010; Tashiro et al., 2011, 2015). The series of research studies has yielded the following insights: (1) slip failure and long-term settlement occur in grounds comprising of soft soils that possess low-permeability and can easily cause rapid plastic compression with softening when subjected to loads exceeding their consolidation yield stress (i.e., in terms of the SYS Cam-clay model, highly structured soils that undergo rapid structural degradation); (2) when a ground containing such soft soil is loading with loads exceeding its consolidation yield stress, the implementation of appropriate pre-countermeasures, such as ground improvement or slow banking, is effective for reducing the total costs, including maintenance and management costs, over the entirety of the embankment lifecycle; and (3) ground improvement by installing vertical drains is an effective pre-construction countermeasure for increasing ground stability and reducing residual settlement.

In recent years, vacuum consolidation has come to be widely applied in combination with vertical drains in cases where embankments have to be loaded quickly to shorten the construction period or when ultra-soft soils, such as peat or reclaimed clay, exist near the ground surface (Cogno et al., 1994; Bergado et al., 1998; Chai et al., 2005, 2006, 2008; Rujikiatkamjorn et al., 2007; Arijayarathna et al., 2010; Osorio et al., 2010; Kosaka et al., 2011; Mersi and Khan, 2012; Karunawardena and Toki, 2013). A remarkable feature of vacuum consolidation is the inward deformation (towards the middle of the improved area) resulting from the application of negative excess pore water pressure. It is expected that, in addition to strengthening through preloading, this deformation will contribute to increased stability by offsetting the outward deformation that occurs during embankment loading. At the same time, depending on the ground conditions, this deformation can affect a large area of the surrounding ground. For this reason, it is necessary to accurately model the pertinent aspects of the construction method and, based on predictions of ground behaviors that are likely to occur, to set appropriate construction conditions including drain spacing, improvement area, and the duration of vacuum loading, etc.

In the practical design of vacuum consolidation, the reduction in pore water pressure due to vacuum loading is often replaced by an equivalent surcharge load, which enables the use of a simple, one-dimensional consolidation calculation based on the solution by Barron (1948). However, in order to account for the inward deformation characteristic of vacuum consolidation, it is desirable to perform a finite element analysis in multiple dimensions. In a multiple-dimensional finite element analysis, directly simulating the vertical drain by employing a fine mesh (Indraratna et al., 2004, 2005; Saowapakpiboon et al., 2011) requires a considerable number of elements. For this reason, a macroscopic method is needed to describe the improved effect depending on the drain spacing and the permeability.

The most common macroscopic method used to represent the effect of vertical drains is the mass-permeability method (Asaoka et al., 1995) whereby the permeability of the ground, including vertical drains, is expressed in an inverse analysis as a mass property. In contrast, the macro-element method proposed by Sekiguchi et al. (1986) allows the effect of a vertical drain to be accounted for even under two-dimensional plane strain conditions by adding the water absorption function of the drain to each element in the improved area. Endeavoring to further extend the function of the macro-element method, the authors recently proposed a macro-element method with water absorption and discharge functions of the drain by treating the water pressure in the drain as an unknown and adding a continuity equation for the drain to the governing equations (Yamada et al., 2015, see Appendix A). They implemented this method (Noda et al., 2015) in the GEOASIA soil–water coupled finite deformation analysis code (Asaoka and Noda, 2007; Noda et al., 2008a,b) capable of accounting for inertial forces. The accuracy of the proposed macro-element method was verified by comparing the simulation results with those by the “exact model” in which a drain is directly modeled by finite element meshes with higher permeability. In addition, the proposed macro-element method was applied to simulate vacuum consolidation on a virtual ground with clay and sand. This method resulted in the natural reproduction of the well-resistance phenomenon under specific conditions by solving the water pressure in the drain. In addition, an advantage of this proposed macro-element method is that the mesh width does not have to be matched to the drain spacing; i.e., the total number of finite elements could be remarkably reduced and the effects of drain spacing could be evaluated using the same mesh.

The first objective of this paper was to validate the ability of the proposed method to accurately simulate the “actual” behavior observed in the field. The simulation results were compared with the actual measurements for the embankment loading of a soft peat ground improved with vertical drains and vacuum consolidation. After simulating the construction history, the permeability of the drain was sought as the single fitting parameter to reproduce the observed ground settlement. As a result, it was found that the proposed method was able to comprehensively and closely reproduce the ground behavior, including the deformation of the surrounding ground and the pore water pressure distribution in the ground profile. In addition, at the actual embankment site, widespread settlement of the area surrounding the test embankment was observed following vacuum loading. It was believed that this settlement could be attributed to the existence of a middle sand layer spanning the entire improvement area. As such, in this paper, the effect of a middle sand layer in vacuum consolidation was also analyzed using the proposed method. Through a comparison with a conventional macroscopic method, such as the mass-permeability method and the macro-element method that treats the water pressure in the drains as a known, the superiority of the proposed method to simulate the multi-layered ground, especially in the case of a ground that includes a middle sand layer, was shown.
The second objective of this paper was to numerically investigate the effects of vertical drains and vacuum consolidation with embankment loading on a soft ground, focusing particularly on the influence of drain spacing. In this case, a softer ground than that of the actual embankment site with alternating peat and clay layers up to the ground surface was modeled to represent a typical ground to which vacuum consolidation would be applied. As a result of the calculations by the above-validated method, it was found that, although vacuum consolidation is effective in cases where there is a need to limit the deformation of the surrounding ground, vertical drains alone can reduce residual settlement to the same degree as vacuum consolidation, provided that the drain spacing is appropriately reduced.

2. Validation of the accuracy of the proposed method based on simulating actual embankment loading

2.1. Overview of the ground being modeled

In order to validate the ability of the proposed method to accurately simulate the actual ground behavior, an actual soft peat ground improved with vertical drains and vacuum consolidation was simulated in this paper. Fig. 1 shows a cross-section of the ground in the Mukasa area (construction was started in 2005; the road was put into service in 2014) of the Maizuru–Wakasa Expressway that was modeled. The ground in this area comprises thick deposits of peat and clay and represents an ultra-soft ground that is rare even in Japan. A test embankment (left side of Fig. 1) was constructed on the site in 2006 in order to identify countermeasures to potential problems associated with embankment loading on a soft ground. In the case of this test embankment, massive settlement exceeding 11 m occurred, which also had a substantial effect on the surrounding ground. In a previous study (Tashiro et al., 2015), using the analysis code GEOASIA with the mass-permeability method, the authors performed a numerical analysis to describe the elasto-plastic behavior of peat, to reproduce and predict the large-scale settlement up to that point and in the future, and also to propose countermeasures to settlement. In this paper, simulations were conducted for the peat ground underlying an embankment located approximately 300 m from the Tsuruga side of the test embankment (right side of Fig. 1) that was subjected to vacuum consolidation in conjunction with vertical drains in January of 2012 in order to reduce construction time.

Fig. 2 shows the distributions of measured values for pore water pressure \( u \) and consolidation yield stress \( p_c \), and estimated initial pore water pressure \( u_0 \) and initial effective overburden stress \( \sigma_{vo} \) for the ground in the vicinity of the test embankment and the target embankment for the current study. It is known from previous research (Tashiro et al., 2015) that, due to the artesian pressure of the valley bottom created by fault movement, the Ac2u and deeper layers of the test embankment comprise successive thick peat deposits characterized by low consolidation yield stress and extremely high compressibility.

A massive settlement in excess of 11 m occurred because a stress state was created for the loaded test embankment that substantially exceeded the consolidation yield stress of the deep peat layers. Based on the results of the numerical analysis in the previous research (Tashiro et al., 2015), it is predicted that residual settlement in the order of 1.5 m will continue over the next 60 or so years. However, it was confirmed in both site and laboratory experiments that the ground under this study’s target embankment is only minimally affected by the artesian conditions, and therefore, that the deep peat layers possess sufficiently large consolidation yield stress. In addition, it was confirmed that alternating clay and sand layers exist in the middle of the ground profile. However, laboratory experiments demonstrated that the shallow Ac1 and Apt 2 layers below both the test embankment and the present study’s target embankment comprise soil of similar type and condition since they are not affected by the artesian conditions. Considering the above points, it is predicted that, although there may be problems associated with the stability and settlement of the shallow ground layers, there is little possibility that the target embankment simulated in this study will undergo the same kind of large-scale delayed settlement as the test embankment.

Fig. 1. Schematic outline of soil strata in the Mukasa area (longitudinal section).
Fig. 2. Estimated initial distributions of pore water pressure and vertical effective pressure.

Fig. 3. Soil profile and measurement points (cross-section).
2.2. Analysis conditions

The cross-section of the ground profile and the finite element mesh and the boundary conditions used in the analysis are shown in Figs. 3 and 4, respectively. Although the thickness of the layers in the actual profile were observed to differ slightly from left to right, given that the settlement amount and pore water pressure were only measured near the center of the embankment, for simplicity, the ground directly under the center of the embankment was modeled and all the layers were assumed to be horizontally stratified. The loading history for the center of the embankment was reproduced as faithfully as possible. In the actual embankment, a vacuum consolidation method with an airtight sheet (Association of Vacuum Consolidation Technology, 2013) was utilized to reduce the construction time. Plastic board drains (PBD), with a width of 100 mm and a thickness of 7 mm, were installed to a depth of 20 m in a square pattern with a drain spacing of 0.7 m. One month after the start of the vacuum loading at approximately 60 kPa, the embankment was built up at a rate of embankment thickness 8 cm/day to a total height of 8 m. Vacuum loading was stopped approximately 2 months thereafter. In the analysis, the embankment and underlying ground were assumed to be fully saturated, and embankment loading was simulated by adding elasto-plastic elements on top of the ground elements (Takaine et al., 2010). To simulate the ground improvement due to the vertical drains, the macro-element method was applied to the elements corresponding to the drain-improved area. The diameter of equivalent soil cylinder \( d_c \) and the equivalent diameter of drain \( d_w \) were both converted based on the cross-sectional area. Vacuum consolidation was simulated by assigning a permeable boundary condition that reduces the water pressure to the boundary corresponding to the inside (the ground side to which the macro-element method is applied) of the airtight sheet (the green line in Fig. 4) and assigning an impermeable boundary to the outside of the sheet (embankment side).

As in the previous research on the test embankment (Tashiro et al., 2015), the material constants and initial conditions of the ground were determined based on laboratory experiments conducted on samples collected in-situ. Several examples of this are shown in Fig. 5. The SYS Cam-clay model was used as the constitutive model for the soil skeleton of all soil materials. However, given that the actual values for all the ground layers were not available from mechanical tests, a number of ground layers (i.e., As1 and As2; Apt2 and Ac2-1; Ac3-u, Ac3, and Ac4 in Fig. 3) were assumed to be of the “same type” based on the results of physical tests. In addition, due to the high inhomogeneity, the sensitivity to disturbance and the high compressibility of the in-situ peat, the experimental results that could not be considered to be homogeneous element behavior with soil of the same type, such as the results for Dpt1 under the highest confining pressure, as shown in Fig. 5(b), were not taken into consideration when determining the material constants by simulation. Furthermore, because mechanical tests were not performed on samples collected from middle sand layers As3, As4, and As5, these layers were assigned material constants for silica sand no. 6 to represent typical sand. The material constants are shown in Table 1, and the distribution of estimated initial conditions is presented in Fig. 6. For simplicity, it was assumed that the permeability coefficient \( k \) for each ground layer was isotropic and logarithmically related to void ratio \( e \) in the manner expressed in (Taylor, 1948)

\[
e = C_k \ln \frac{k}{k_0} + e_0,
\]

(1)
where $C_k$ is the coefficient of change in permeability. As shown in Table 2, $C_k$, $k_0$, and $e_0$ were determined based on the results of consolidation tests on undisturbed samples.

In this analysis, after setting all other ground parameters, the permeability coefficient of the drain, $k_w$, was utilized as the lone fitting parameter. Based on the specifications for PBD (Association of Vacuum Consolidation Technology, 2013), the value for $k_w$ resulting in the best fit to the observed settlement at the center of the embankment, was sought from within the range of $1.0 \times 10^{-2} - 1.0 \times 10^1$ cm/s. Incidentally, the influence on consolidation, such as disturbance resulting from the installation of drains, could be automatically considered when the permeability coefficient of the drains ($k_w$) is determined by back analysis, although “the smear effect” of the drains themselves is not taken into account in the proposed macro-element method.

### 2.3. Validation of the simulation accuracy of the proposed method

Figs. 7 and 8 show the results of the simulations. For comparison, the simulation results using the following three methods are also shown. Table 3 presents the material parameters

**Table 1**

<table>
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<tr>
<th>Soil layer</th>
<th>As1</th>
<th>Ac1</th>
<th>Apt2</th>
<th>Ac2-1</th>
<th>Ac2-2</th>
<th>Apt5</th>
<th>As3</th>
<th>Ac3u</th>
<th>Ac3</th>
<th>Ac4</th>
<th>Dpt1</th>
<th>Dpt2</th>
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<td>Elasto-plastic parameters</td>
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<tr>
<td>Compression index $\lambda$</td>
<td>0.15</td>
<td>0.37</td>
<td>0.31</td>
<td>0.39</td>
<td>0.73</td>
<td>0.05</td>
<td>0.24</td>
<td>0.48</td>
<td>0.40</td>
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<td>Swelling index $\kappa$</td>
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<td>0.055</td>
<td>0.040</td>
<td>0.045</td>
<td>0.045</td>
<td>0.012</td>
<td>0.030</td>
<td>0.050</td>
<td>0.045</td>
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<td>Critical state index M</td>
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<td>1.55</td>
<td>1.20</td>
<td>2.40</td>
<td>2.35</td>
<td>1.55</td>
<td>1.50</td>
<td>2.55</td>
<td>2.10</td>
<td></td>
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<td>NCL intercept N</td>
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<td>2.90</td>
<td>2.75</td>
<td>2.88</td>
<td>4.10</td>
<td>1.98</td>
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<td>2.90</td>
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<td>Poisson’s ratio $\nu$</td>
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<td>0.35</td>
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<tr>
<td>Degradation index of OC $m$</td>
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<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
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<td>Degradation index of structure $a$</td>
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<td>0.37</td>
<td>0.40</td>
<td>0.25</td>
<td>0.35</td>
<td>1.00</td>
<td>0.50</td>
<td>0.30</td>
<td>0.40</td>
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<tr>
<td>$b$</td>
<td>1.00</td>
<td>0.80</td>
<td>0.80</td>
<td>0.90</td>
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<td>1.00</td>
<td>0.95</td>
<td>0.90</td>
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<td>$c_r$</td>
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<tr>
<td>Rotational hardening index $b_{h}$</td>
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<td>0.05</td>
<td>0.03</td>
<td>0.07</td>
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<td>0.05</td>
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<tr>
<td>Limitation of rotational hardening $m_{bh}$</td>
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<td>1.0</td>
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<td>1.0</td>
<td>0.7</td>
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<td>1.0</td>
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<tr>
<td>Soil particle density $\rho_s$ (t/m$^3$)</td>
<td>2.65</td>
<td>2.38</td>
<td>2.42</td>
<td>2.17</td>
<td>1.84</td>
<td>2.66</td>
<td>2.57</td>
<td>1.96</td>
<td>2.16</td>
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</table>

Fig. 5. Examples of laboratory test results and simulation using the SYS Cam-clay model. (a) Ac1. (b) Dpt1.
expressing the improvement effect of the vertical drains used in each of these methods.

(1) The vertical drain improvement is expressed using a single equivalent coefficient of permeability for the ground (mass-permeability method).

(2) As with the conventional macro-element method (Sekiguchi et al., 1986), the drain permeability is approximated to be infinity (i.e., macro-element method where the drain permeability is treated as a known).

(3) In the newly proposed macro-element method with water absorption and discharge functions, which provides a solution for the water pressure in the drain (i.e., macro-element method), the drain permeability is treated as an unknown.

Each of these methods is already capable of simulating the settlement of the ground surface. However, because the (1) mass-permeability method does not describe the transmission of vacuum pressure through the vertical drain, the effect of the vacuum loading on the shallow layers of the improved area is overestimated, whereas the effect on the deep layers is underestimated. When thinking about ground stability problems, such a result would be on the dangerous side. Furthermore, the method does not simulate the widespread settlement of the ground surrounding the improved area. Meanwhile, both macro-element methods (2) and (3) simulated a permeability-dependent reduction in pore water pressure in all the ground layers down to the deep layers of the improved area by vacuum loading. In particular, the macro-element method proposed by the authors (3) (Yamada et al., 2015, see Appendix A) naturally simulated a type of well-resistance phenomena in which the reduction in pore water pressure becomes increasingly difficult in deeper layers. In addition, it was confirmed that the method more comprehensively and accurately simulates all types of observed ground behaviors, including the temporal change in pore water pressure, the horizontal displacement directly under the toe of the embankment slope, and the settlement of the surrounding ground.

When the simulation of the target embankment was allowed to continue using the same parameters, it was found that consolidation within the vertical drains was completed early on. Although residual settlement of the unimproved deep layers was observed to occur, the amount of settlement was predicted to be sufficiently small so as not to be problematic at the time the embankment would be put into service (approximately 2 years after the completion of the embankment construction).

2.4. Impact of the middle sand layers

After vacuum consolidation of the target embankment was started, settlement up to 5 cm was observed over a wide area...
located approximately 50 m from the embankment toe of the
slope. Subsequent investigation indicated that this settlement
may have been due to the presence of the thin middle sand
layers (As1 and As2) spanning the entire improvement area.

In order to demonstrate that the settlement of the surround-
ing ground was indeed due to the presence of these middle
sand layers, simulations were performed using the proposed
macro-element method (3), the simulation accuracy of which
was validated above, after replacing the two sand layers (As1
and As2) with the underlying clay layers (Ac1 and Ac2-1). Figs. 9
and 10 show the settlement of the surrounding ground
and the distribution of the vacuum pressure (negative pore
water pressure), respectively, during vacuum consolidation. It
was demonstrated that the transmission of vacuum pressure to
a wide area beyond the improved area through the middle sand
layers results in the settlement, and not the uplift, of the
surrounding ground even during embankment loading.

3. Effects of drain spacing on ground improvement using
vertical drains and vacuum consolidation

An advantage of the proposed macro-element method, the
simulation accuracy of which was validated in the previous
section, is that the mesh width does not have to be matched to
the drain spacing. In other words, it is possible to evaluate the
effect of drain spacing using the same mesh. Therefore, in this
section, calculations were conducted to investigate the influ-
ence of drain spacing on the outcome of ground improvement
using vertical drains and vacuum consolidation during the
embankment loading of a soft ground.

Here, a softer ground than that in the previous simulations,
with alternating peat and clay layers up to the ground surface,
was modeled to represent the typical ground where vacuum
consolidation would be applied. Specifically, all the sand
layers of the ground shown in Fig. 4, which were subject to
analysis in the previous section, were replaced by underlying
clay or peat layers, resulting in the ground model shown in
Fig. 11. Simulations were performed and the results were
compared for the following 5 cases:

1. : no ground improvement
2. : vertical drains with 1.5 m spacing
3. : vertical drains with 1.0 m spacing
4. : vertical drains with 0.7 m spacing
5. : vertical drains with 1.0 m spacing, combined with vacuum
consolidation (70 kPa).

For simplicity, a simpler embankment shape and loading
history than for the analyses in the previous section were
assumed. As in the previous analyses, the depth of the
improved area was set at 20 m. The width of the improved
area was set to be the entire embankment width including the
counterweight fill. As can be seen from the Case 1 simulation
results (Fig. 13(a)), this was done because the large-scale shear
deforation of the softer ground being modeled occurs even
under the counterweight fill. The final embankment level
(height from initial ground level) is usually controlled without
considering the amount of settlement during loading in
practical construction projects. However, in order to compare
the final settlement directly under the same total load for each
case, the embankment thickness (embankment height + settle-
ment) at the completion of the embankment construction were
set to be the same for each case. The material constants and
initial values of the ground, and the vertical drain permeability
coefficients from the simulations in the previous section, were
used in the present calculations without modification.

Fig. 12 compares the ground surface settlement at the center
of the embankment predicted for each of the cases. In Case 1,
where no ground improvement is employed, there is a rapid
increase in settlement rate during embankment loading, accompanied by the occurrence of large-scale circular shear deformation in the shallow, low-permeability, low-strength Ac1 and Apt2 layers, which can be seen in Fig. 13(a). Although the main focus of this paper is on the quasi-static problem of consolidation, by using a code with an inertia term that is capable of handling dynamic problems, depending on the circumstances, it is possible to describe such slip failure.

Fig. 8. Validation of reproducibility. (a) Isochrones of water pressure change inside of improvement area. (b) Settlement of the surrounding ground. (c) Lateral displacement at the toe of embankment slope.
under load-controlled conditions (Noda et al., 2008b; Takaine et al., 2010; Nakano et al., 2010; Yamada and Noda, 2013; and Tashiro et al., 2015).

Meanwhile, it was demonstrated that ground improvement using vertical drains is effective in preventing slippage during loading. In cases such as Case 2, where the drain spacing is too wide to provide adequate drainage, although it is possible to prevent fatal slip failure during loading, as can be seen in Fig. 14, large-scale outward horizontal displacement and uplift of the ground adjacent to the improved area occur as a result of the large shear deformation of the shallow layers in the improved area. As can be seen in Table 4 and Fig. 14, by reducing the spacing

Table 3
Parameters representing improvement effect by vertical drains.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>(1) Mass-permeability</th>
<th>(2) Conventional macro-element</th>
<th>(3) Newly proposed macro-element</th>
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<tbody>
<tr>
<td>Equivalent coefficient of permeability of improved area $k_E$ (cm/s)</td>
<td>$2.5 \times 10^{-4}$</td>
<td>$\infty$</td>
<td>$4.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>Coefficient of permeability of vertical drains $k_v$ (cm/s)</td>
<td>$-\infty$</td>
<td>$4.0 \times 10^{-2}$</td>
<td>$-\infty$</td>
</tr>
</tbody>
</table>

Fig. 9. Effect of middle sand layer on the surrounding settlement.

Fig. 10. Distribution of negative pore water pressures during vacuum consolidation and embankment loading. (1) Simulation (2) Replacing sand with clay.

Fig. 11. Model ground assumed to be under softer conditions.
between the vertical drains, the total settlement, the residual settlement, and the deformation of the surrounding ground are reduced, enabling a more stable construction. In the ground modeled in this study, reducing the drain spacing from 1.0 to 0.7 m (Case 4) yielded the same reduction in residual settlement as combining vacuum consolidation (Case 5). However, even when drain spacing was sufficiently narrow, due to the lack of inward consolidation associated with vacuum consolidation, ground improvement using vertical drains alone did not necessarily reduce the outward horizontal displacement to the same degree as ground improvement using both vertical drains and vacuum consolidation.

4. Discussion

In this section, the results presented in Sections 2 and 3 are discussed with the aim of coming up with practical recommendations for the application of vacuum consolidation during embankment loading on a soft ground.

Given the same drain spacing, the use of vacuum consolidation in combination with vertical drains reduces residual settlement to a greater degree than the use of vertical drains alone. Nevertheless, the total settlement amount is greater because the ground does not completely return to its previous state even after vacuum loading is stopped. Meanwhile, when employing ground improvement using vertical drains alone, if a sufficiently narrow drain spacing is utilized so that the drains provide adequate drainage relative to the ground’s permeability, it is possible to not only enhance ground stability, but also reduce the residual settlement and the total settlement.

Table 5 shows the estimated construction costs for Cases 2 through 5, discussed in Section 3, based on the actual construction costs for the target embankment simulated in Section 2. It was assumed that PBD cost 200 JPY/m and that vacuum consolidation costs an additional 10,000 JPY/m². Under the conditions simulated in this study, comparing Cases 4 and 5,

Table 4
Comparison of settlements.

<table>
<thead>
<tr>
<th>Case</th>
<th>Drain spacing (m)</th>
<th>Total settlement (m)</th>
<th>Residual settlement a (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.5</td>
<td>6.03</td>
<td>173</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>5.92</td>
<td>126</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>5.63</td>
<td>93</td>
</tr>
<tr>
<td>5</td>
<td>1.0 (+ Vacuum)</td>
<td>5.88</td>
<td>85</td>
</tr>
</tbody>
</table>

*aDefined as the settlement measured 72 days after the end of embankment loading (corresponding to the end of vacuum consolidation).

Table 5
Comparison of construction costs (per unit area).

<table>
<thead>
<tr>
<th>Case</th>
<th>Drain spacing (m)</th>
<th>Drain length (m)</th>
<th>Construction cost (thousand yen/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.5</td>
<td>20</td>
<td>1.8</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>20</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>20</td>
<td>8.1</td>
</tr>
<tr>
<td>5</td>
<td>1.0 (+ Vacuum)</td>
<td>20</td>
<td>14.0</td>
</tr>
</tbody>
</table>

Fig. 12. Comparison of ground settlements.

Fig. 13. Distributions of shear strain. (a) Case 1: No improvement (Circular slip during embankment loading), (b) Case 4: 0.7 m-spacing PVD (End of consolidation).

Fig. 14. Comparison of surrounding deformations at the end of loading.
which yielded the same magnitude of settlement reduction, the additional use of vacuum consolidation approximately doubles construction costs. Furthermore, although a reduction in construction time through rapid loading is often touted as one of the advantages of vacuum consolidation, in reality, vacuum consolidation requires substantial set-up time prior to the application of the vacuum load in order to lay the airtight sheet, set up the vacuum pump, etc. If, in the end, the construction time is the same, it would be better to install vertical drains at a high density and to employ slow banking.

However, because vertical drains alone do not cause inward deformation, they are not able to reduce horizontal displacement to the same extent as vacuum consolidation used in combination with vertical drains, even if vertical drains are installed at a high density. For this reason, vacuum consolidation is effective when there are structures near the area to be improved that must be protected or when the aim is to minimize the impact on the surrounding ground.

Another consideration when deciding whether to also use vacuum consolidation is whether the soft ground contains a middle sand layer. In general, the presence of a middle sand layer can be expected to accelerate consolidation and to contribute to increased stability. However, when performing vacuum consolidation, depending on the ground conditions, the middle sand layer may cause the effective vacuum pressure to be lower than the design value. In such cases, it may be necessary to reconsider the stability/settlement management including the embankment construction rate and the surcharge embankment height. In addition, as discussed in Section 2, transmission of the vacuum pressure through the middle sand can cause the wide-scale settlement of the ground surrounding the improved area. As such, when using vacuum consolidation in combination with vertical drains, it is important that a more careful ground investigation be conducted prior to the ground improvement. When a middle sand layer suspected of being continuous is encountered, it is necessary to implement countermeasures including the application of waterproof sealing material to the surface of the drains in the vicinity of the sand layer, the installation of sheet piling, or the making of the more fundamental decision not to use vacuum consolidation itself. As demonstrated in this study, one solution to the above problem is to use vertical drains only with narrow spacing. In addition, the proposed macro-element method, whose simulation accuracy was validated in this paper, is an effective method for quantitatively predicting the impact of middle sand layers.

5. Conclusions

In this study, the simulation accuracy of the macro-element method with water absorption and discharge functions proposed by the authors, implemented in a soil–water coupled finite deformation analysis code, was validated by simulating an actual site. In addition, at the target site, the widespread settlement of the ground surrounding the embankment was observed after vacuum loading, which was believed to be due to the presence of a middle sand layer spanning the entire improved area. Therefore, the effect of a middle sand layer was investigated using the proposed method. Additional calculations were conducted using a ground model for a ground softer than at the actual site, which represented a typical ground to which vacuum consolidation would be generally applied. In these simulations, the effect of vertical drains and vacuum consolidation were investigated, with a particular focus on the influence of drain spacing. The main findings of this paper are summarized as follows:

(1) The macro-element method with water absorption and discharge functions proposed by the authors is capable of comprehensively and closely simulating a range in ground behaviors including the temporal change in pore water pressure, the horizontal displacement of the ground under the toe of the embankment slope, and the settlement of the surrounding ground in consolidation problems involving the embankment loading of multi-layered ground improved with vertical drains and vacuum consolidation.

(2) When a middle sand layer is present across the entire improved area, the mass-permeability method (whereby an equivalent coefficient of permeability is assigned to the ground improved using vertical drains) is unable to simulate the reduction in pore water pressure of the ground adjacent to the improved area and the widespread settlement resulting therefrom. Meanwhile, the macro-element method that treats the water pressure in the drains as a known may overestimate the impact of vacuum consolidation.

(3) Even in the case of ground improvement using vertical drains alone (i.e., without vacuum consolidation), it is possible to increase the stability and to reduce the deformation of the surrounding ground by selecting an appropriate drain spacing that provides sufficient drainage for the ground’s permeability. In addition, the use of vertical drains only with the appropriate spacing can yield the same reduction in residual settlement as the case of vacuum consolidation combined with vertical drains.

(4) Vacuum consolidation is effective in cases where it is necessary to minimize the residual settlement and the deformation (in particular, outward horizontal displacement) of the surrounding ground.

(5) When determining the vertical drain spacing and whether to also use 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 example, the ground adjacent to the improved area, construction costs, and construction time. The macro-element method proposed by the authors herein is capable of quantitatively simulating/evaluating the effects of various factors and should prove to be an effective tool for making comprehensive decisions in actual practice.

Appendix A. Governing equations of the soil–water finite deformation analysis applied with the macro-element method with water absorption and discharge functions for vertical drains (For details, referred to Noda et al., 2015)

The soil–water finite deformation analysis with inertia terms, developed by Noda et al. (2008a), employs a so-called u-p formulation to obtain the nodal displacement velocity vector...
{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

\[
M \{ \ddot{v}^N \} + K \{ v^N \} - L^T \ddot{u} = \{ f \} \tag{A1}
\]

where \( M \) is the mass matrix, \( K \) is the tangent stiffness matrix, \( L \) is the matrix for converting \( \{ v^N \} \) to the element volume change rate, \( \{ f \} \) is the nodal force rate vector, \( \{ v^N \} \) and \( \{ \dot{v}^N \} \) denote the nodal acceleration and jerk vectors, \( h \) and \( h_i \) represent the total heads corresponding to the representative values for water pressure for an element and adjacent elements, respectively, \( k \) is the permeability coefficient for the ground, \( g \) is the magnitude of the gravitational acceleration, \( \alpha \) is the coefficient of pore water flow to adjacent elements, \( \rho_w \) is the density of water, and \( m \) is the number of boundary surfaces for each element. The first term on the left-hand side of Eqs. (A1) and (A2) is the one which vanishes when inertia forces do not work.

In the macro-element method proposed by Yamada et al. (2015), the water absorption and discharge functions of vertical drains were introduced into the above analytical method by the following procedures.

First, to incorporate the water absorption function of the vertical drains into each element, the soil-to-drain pore water flow rate is added to the right-hand side of Eq. (A2), yielding the following expression:

\[
\frac{k}{g} L \{ \ddot{v}^N \} - L \{ v^N \} = \sum_{i=1}^{m} \alpha_i (h - h_i) \rho_w g + k (h - h_D) \rho_w g \tag{A3}
\]

Eq. (A3) is called the soil–water continuity equation and replaces Eq. (A2) as a governing equation. Here, \( h_D \) is the representative value for total head in the drain for each element. \( \kappa \) is the coefficient of pore water flow from the soil to the drain and given by the following equations:

\[
\kappa = \frac{8kV}{F(n)d_e^2 \rho_w g}, \tag{A4}
\]

\[
F(n) = \frac{n^2}{n^2 - 1} \ln n - \frac{3n^2 - 1}{4n^2}, \quad n = \frac{d_e}{d_w}. \tag{A5}
\]

in which \( V \) is the current volume of each element. \( d_e \) and \( d_w \) represent the equivalent diameter and diameter of circular drain, respectively, and are treated as material constants.

Next, to incorporate the discharge function of the drains into the macro-element method, the following continuity equation for the drain is introduced to the governing equations, on the assumption that the mesh division from the top to the bottom of the improved region is initially divided up approximately vertically:

\[
\kappa (h - h_D) \rho_w g = \sum_{j=1}^{2} \beta_j (h_D - h_D_j) \rho_w g \tag{A6}
\]

where \( \beta_j \) is the coefficient of water flow through the virtual drain contained in each element, and \( h_D \) is the total head of the drain contained in the elements above and below the macro-element. For the sake of simplicity, it is assumed that water flow through the drain obeys Darcy’s law. Bearing in mind that the ratio of the cross-sectional area of the virtual drain to the area of the boundary surface between the elements connected above and below is \( 1/n^2 \), \( \beta_j \) is given by the following equation:

\[
\beta_j = \frac{k_w l_j}{l^2} \frac{m_i s_j}{n^2} \tag{A7}
\]

where each symbol is defined as illustrated in Fig. A1. \( k_w \) is the permeability coefficient for a circular drain and is treated as a material constant. The boundary conditions for Eq. (A6) are handled in the same manner as the hydraulic boundary conditions for Eq. (A2).

Consequently, Eqs. (A1), (A3) and (A5) represent the governing equations when the macro-element method is applied. Solving these equations simultaneously yields \( \{ v^N \} \), \( u \), and \( u_D \), which is the water pressure corresponding to \( h_D \).

References


