Numerical Analysis of Drain Spacing Effects on Ground Improvement Using Vertical Drain/Vacuum Consolidation

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1. Introduction

Ground improvement is often performed when an embankment is constructed on a soft ground to prevent slip failure during loading or substantial residual settlement possibly occurring after entry-into-service. Vertical drain is one of the most effective and popular method as reported from field large-scale test and numerical analysis (Tashiro et al., 2015). Recently, vacuum consolidation has been widely applied together with vertical drains to i shorten the construction period or when ultra-soft soils such as peat exist near the ground surface.

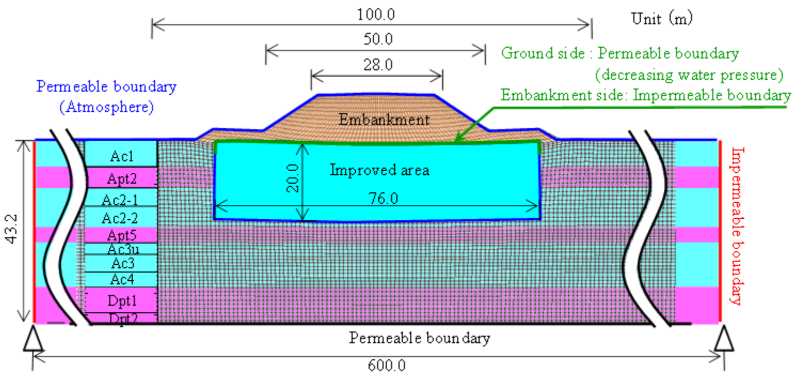


Fig.1 Finite element mesh and boundary conditions

This study applied a new modified macro element method with water absorption and discharge function proposed by the authors (Yamada et al., 2013) incorporated in finite deformation geo-analysis code ***GEOASIA*** (Asaoka and Noda, 2007) to investigate the effects of drain spacing on the ground improvement using vertical drain (PVD)/vacuum consolidation. An advantage of this new proposed macro element is that the size of elements does not have to matched to drain spacing, therefore a series of calculation can be carried on a same mesh (Fig. 1).

2. Analysis conditions

Fig. 1 shows the finite element mesh and boundary conditions used in this study, in which an approximate 40m soft ground underlying embankment with alternating peat and clay layers up to the ground surface was modelled, to represent the typical ground where vacuum consolidation would be applied. PVDs were assumed to be installed from the ground surface with a length of approximately 20 m arranged in a square pattern, and modelled by applying the macro-element method to elements corresponding to the drain-improved area. In simulating the vacuum consolidation, the air-tight sheet was modelled by boundary conditions where the ground side was allocated to be drained condition to simulate applying/stopping vacuum pressure; meanwhile the embankment side is undrained condition. Material constants, initial conditions of the ground and the permeability of vertical drain were used in the previous simulations of the Mukasa area of the Maizuru-Wakasa Expressway (Nguyen et al., 2014).

Simulations were performed for the following 5 cases:

Case 1: no ground improvement, Case 2: PVDs at spacing of 1.5 m,

Case 3: PVDs at spacing of 1.0 m, Case 4: PVDs at spacing of 0.7m,

Case 5: PVDs at 1.0m spacing with vacuum consolidation.

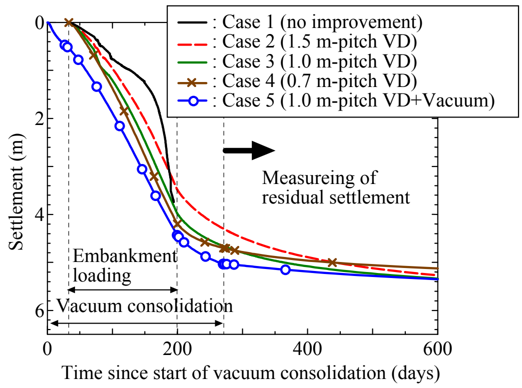
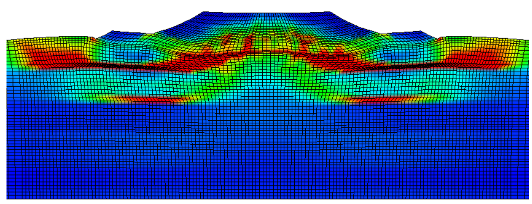
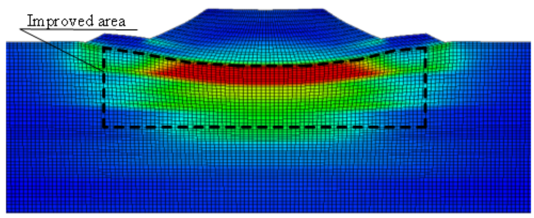


Fig.2 Comparison of ground settlements



(a) Case 1: No improvement
(Circular slip during embanking)



(b) Case 4: 0.7 m-pitch PVD (End of consolidation)

Fig. 3 Distributions of shear strain

To ensure that the load conditions were the same for each case, the embankment thickness (embankment height + settlement) at completion of embanking were set to be the same (14.3m) for each case under a simple loading rate (thickness/ time) of 8cm/day. Vacuum pressure (70 kPa) was kept in 27 days before starting embankment loading, and after finish embanking; the vacuum pressure was maintained in 72 days.

3. Calculation results

Fig. 2 compares the ground surface settlement curves at the center of the embankment 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 layers with low-permeability and low-strength (Fig. 3(a)). Meanwhile, it was demonstrated that ground improvement using PVDs 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 fatal slip failure during loading can be prevented, as can be seen in Fig. 4, large-scale outward horizontal displacement and uplift of the ground adjacent to the improved area occurs as a result of large shear deformation of the shallow layers in the improved area. As demonstrated in Table 1 and Fig. 3, by reducing the spacing between vertical drains, total and residual settlements, and deformation of the surrounding ground are reduced, enabling more stable construction. In the modeled ground, reducing the drain spacing from 1.0 to 0.7 m (Case 4) yielded the same decreasing in residual settlement as combining vacuum consolidation (Case 5). However, even spacing was sufficiently narrow, due to the lack of inward displacement associated with vacuum consolidation; horizontal displacement in case of ground improvement using vertical drains alone is not small as much as that of using both vertical drains and vacuum consolidation.

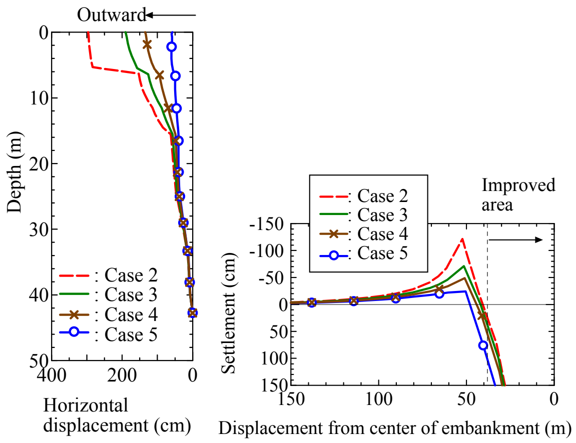


Fig. 4 Surrounding deformations at the end of loading.

Table 1 Comparison of settlements.

Case	Drain spacing (m)	Total settlement (m)	Residual settlement *(m)
2	1.5	6.03	173
3	1.0	5.92	126
4	0.7	5.63	93
5	1.0 (+Vacuum)	5.88	85

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

4. Conclusion

In this study, the simulation results indicated that the ground improvement by PVDs is effective for avoiding a slip failure during loading. However, if drain spacing is too large, the circular shear deformation can occur after the end of loading. The sufficiently small drain spacing could have almost the same effect as combining with vacuum consolidation to promote the dissipation of excess pore water pressure, i.e., to reduce the residual settlement. However, only PVDs could not sufficiently reduce the surrounding deformation, particularly in lateral displacement in comparing to vacuum consolidation. Therefore, selection of the improvement method such as the appropriate drain spacing or the necessity of combination with vacuum consolidation depending on the ground conditions and the peripheral foundations is important.

References

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