Analyzing Embankment Displacement: PVD and Vacuum Consolidation with Sheet Pile Protection

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ABSTRACT

The global widespread adoption of Prefabricated Vertical Drains (PVD) in conjunction with vacuum consolidation is driven by its robust and cost-efficient attributes. However, this construction method is not without challenges, as it has been linked to substantial displacements, posing risks to adjacent structures. Addressing such concerns in a Vietnamese road construction project, this study focuses on the innovative contribution of sheet pile protection as a highly effective solution. Utilizing numerical analysis with an anisotropic model, we examine the impact of sheet pile protection on embankment displacement. Through comparative analysis with field data, our study demonstrates the remarkable efficacy of the sheet pile method in significantly reducing both vertical and lateral settlements. Acting as a protective membrane, it effectively counters suction from the PVD vacuum zone. These findings make a substantial contribution to the field, providing engineers handling similar structural protection scenarios with invaluable insights and a novel approach to mitigating displacements associated with PVD and vacuum consolidation.

Keywords-PVD; vacuum consolidation; sheetpile; lateral displacement

I. INTRODUCTION

PVD, in conjunction with vacuum consolidation, has been widely embraced for its efficient and cost-effective approach in expediting consolidation processes. However, this construction method is not without its challenges, often resulting in substantial lateral and vertical displacements, thereby posing potential risks to adjacent structures. Authors in [1] identified a critical tension cracking zone linked to lateral embankment displacement during vacuum application. Complementing this, authors in [2] conducted field measurements to unravel factors influencing lateral displacement, including construction rate, consolidation rate, and loading. Numerous laboratory tests, including the use of modified triaxial test devices [3, 4, 5], have explored the lateral displacement associated with this technique. Additionally, several studies have proposed straightforward techniques for predicting such displacement Despite the wealth of analytical [8-10] and numerical [1, 6, 7, 12, 13] studies examining vertical and lateral displacements resulting from PVD with vacuum consolidation, a critical aspect remains largely unexplored: the identification of countermeasures to effectively mitigate these substantial displacements. In the analysis of the Bachiem road construction case study, a strategic solution emerged to mitigate displacements linked to embankment construction, employing steel sheet piles. The efficacy of this approach was validated through field measurements, affirming the significant reduction in lateral displacement and the consequent protection of nearby structures. A comprehensive numerical analysis delved into the reinforcement method, uncovering that the sheet pile wall adeptly obstructed pore pressure and applied stresses, ultimately leading to a notable decrease in lateral displacement. These findings not only offer crucial insights for engineers grappling with similar challenges but also furnish compelling evidence supporting the adoption of sheet pile solutions as a protective measure for neighboring structures in their projects.

II. PROJECT DESCRIPTION

The Bachiem project, situated 20 km east of Hochiminh City in southern Vietnam, involved ground improvement for a road using Prefabricated Vertical Drains (PVD) in conjunction with vacuum consolidation, as depicted in Figure 1. The project is located on a soft clay deposit from the Saigon river with depth varying from 10 to 30 m depth. These conditions posed a risk of substantial settlement after construction, necessitating ground improvement to facilitate consolidation and prevent damage to road structures during service. A comprehensive account of the project details can be found in [12]. However, a significant challenge emerged due to the proximity of nearby structures, situated very close to the construction site.

Fig. 1. Project location.

Fig. 2. Construction site with sheet pile protection.

As depicted in Figure 2, the proximity of residential structures to the embankment, with spacing ranging from 2.0 to 6.0 m, raises concerns about potential damage during construction. To address this issue, a solution involving the installation of steel sheet piles at the embankment toe was proposed, extending to a depth of 18 m to protect the nearby buildings. Figure 2 illustrates the on-site implementation of the sheet pile, with the treated zone on the left featuring a geomembrane cover at the surface. The road width was 19.5 m, with a 2.3 m height. The soil profile included layer 1a, consisting of soft to very soft clay from the ground to a depth of 20.5 m, layer 1b with medium clay from 20.5 to 24.0 m, and layer 2 comprising sandy clay from 24.0 to 30.0 m. Ground treatment involved a PVD triangle pattern with a 1.0 m spacing, reaching a depth of 15.0 m. Inclinometers were strategically installed at the toe of the embankment on both the left and right-hand sides, providing critical monitoring points for lateral displacement of the construction process.

III. DISPLACEMENT MEASUREMENT DATA

As evident from Figure 3(a), notable lateral displacement was observed at the end of treatment, particularly on the left side where no reinforcement was implemented. The maximum lateral displacement reached almost 0.5 m towards the embankment, signifying the influence of vacuum pressure inducing suction and creating a similar isotropic state for the treated soil elements beneath the embankment. This phenomenon aligns with the findings reported in laboratory tests and field measurements [2, 4]. Interestingly, this behavior contrasts with conventional embankments subjected to surcharge preloading, where lateral displacement typically moves outward from the embankment due to the imposed stresses from the surcharge load.

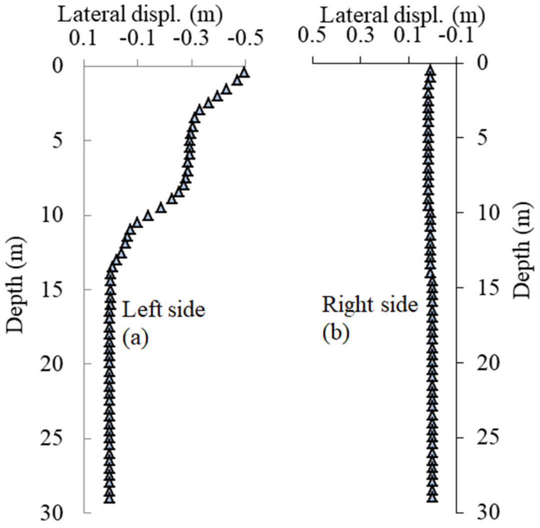

Fig. 3. Lateral displacements at the end of treatment: (a) at the left side of embankment without any reinforcement, (b) at the right side of embankment with sheet pile reinforcement.

Conversely, the field measurements from the right side (Figure 3(b)), reinforced with sheet pile, demonstrated minimal displacement, highlighting the effective role of sheet pile in mitigating the impact of embankment construction enhanced with the PVD vacuum technique. Figure 4(b) illustrates that the lateral displacement near the sheet pile wall reached a maximum value of 0.015 m toward the embankment, a 33 times reduction compared to the displacement on the left-hand side. It is north noting that the effectiveness of sheet pile reinforcement may be largely dependent on the depth of treatment. The treatment depth was 15.0 m, while the length of the sheet pile wall extended to 18.0 m. The data presented in Figure 3(a) show a rapid reduction in lateral displacement on the right side when the treatment depth reached from 10.0 to 15.0 m, suggesting that this depth range can function as a zone restraining displacement for the sheet pile. Consequently, the lateral displacement of the sheet pile exhibited minimal values, as observed in Figure 4(b).

IV. NUMERICAL SIMULATIONS

To comprehensively assess the effectiveness of the reinforcement method, this study conducted numerical simulations. The employed approach involved the anisotropic model of [14] incorporating the rotation of the yield surface, accounting for soil anisotropy. This choice is justified by the characteristics of clay particles and their flocculation during the natural consolidation process, making an anisotropic model a reasonable representation. The parameters used for model validation are detailed in Table I. λ is the compression index, κ is the recompression index, α is the size and inclination of the yield surface, β and μ are the material parameters controlling the rotation rate when yield surface rotate toward direction of applied load, and M is the critical stress ratio in compression (M_c). The critical stress ratio in extension, M_e, was based on the generalization of three dimensional stress trajectories of M assuming dependence on Lod's angle [15].

TABLE I. PARAMETERS OF THE ANISOTROPIC MODEL

Parameter	λ	κ	α	β	μ	M
Value	0.60	0.075	0.62	0.856	5.0	1.3

The constitutive model was implemented into ABAQUS using a UMAT (user-defined material) model. Model validation involved a comparison with the compression and extension results of CkoU, as illustrated in Figures 4 and 5. The soil sample underwent initial Ko consolidation to a mean effective pressure of 119.0 kPa, followed by shear processes. Figure 4 presents a comparison of stress paths, while Figure 5 illustrates the stress-strain relationship. These comparisons serve to highlight the efficacy of the anisotropic model in accurately capturing the stress-strain behavior and stress paths within the current soft soil.

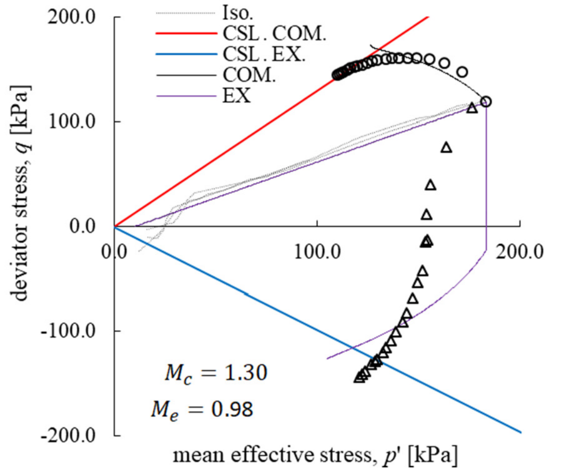

Fig. 4. Comparison of stress path between the simulated and the experimental results.

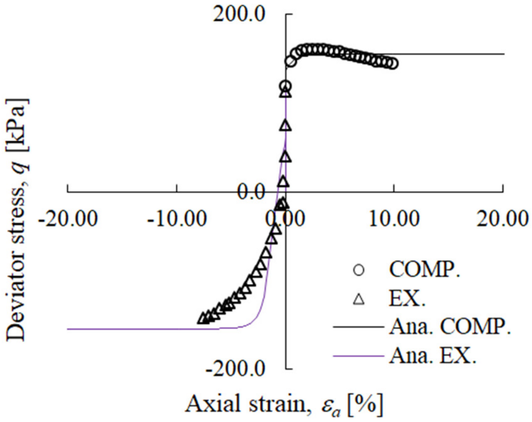

Fig. 5. Comparison of stress-strain between the simulated and the experimental results.

Moreover, the parameters for each soil layer were derived from the details presented in [12], including values such as maximum past pressure, over consolidation ratio, vertical and horizontal permeability for each layer, and the permeability assigned to the treated zone. It is important to highlight that the current approach involved employing the same simulation method for the PVD treated zone, which was replaced with an equivalent soil layer possessing similar properties. However, the vertical permeability for this layer was modified based on [16]. The loading sequence was also outlined in the study by [12]. The sheet pile type NS-SP-IV had sectional area A = 225.5 cm^2/m and moment of inertia I = 56,700 cm^4/m. The simulation for sheet pile employed beam elements with the same value of AI.

V. RESULTS AND DISCUSSION

In Figure 6, a comparison is presented between the settlement values obtained from the Finite Element Method (FEM) results and the actual field data. The FEM results exhibit a commendable agreement with the measured settlement values, affirming the appropriateness of the simulation in accurately capturing the settlement behavior of the treated embankment.

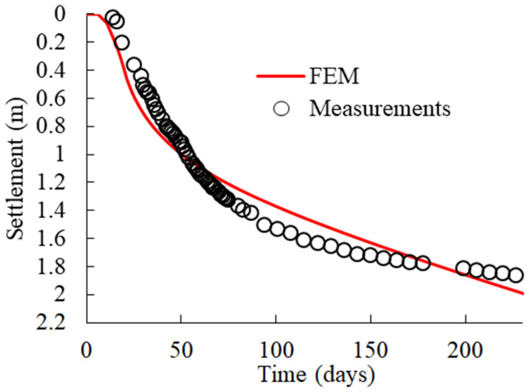

Fig. 6. Comparison of the settlement at the center of the embankment between the FEM results and field measurement.

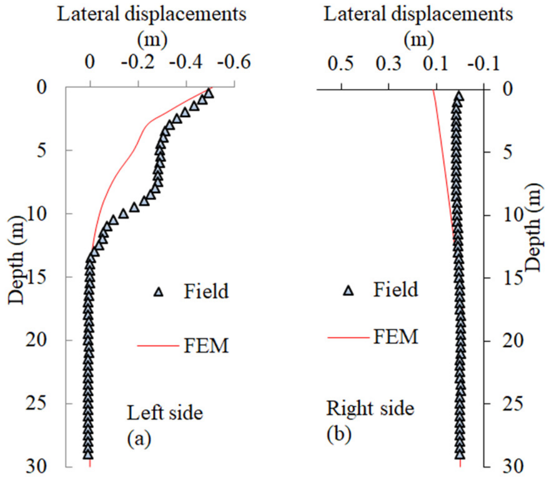

Fig. 7. Comparison of the lateral displacement between the FEM results and field measurements: (a) at the left side of the embankment without any reinforcement, (b) at the right side of the embankment with sheet pile reinforcement.

Figure 7 provides a comparison between the simulated lateral displacements and the field measurement data. The Figure demonstrates that the current simulation effectively captures the lateral displacement observed in the field data. Furthermore, the simulation successfully characterizes the influence of the sheet pile wall in reducing lateral displacements. As depicted in Figure 8, the pore pressure distribution at the end of the construction state (date 240) highlights the efficacy of the sheet pile wall. On the right-hand side of the embankment, the sheet pile effectively obstructed negative pore pressure. Conversely, on the left-hand side, the pore pressure gradually diminished outward from the toe of the embankment. Additionally, Figure 8 illustrates that the maximum negative pore pressure induced by the vacuum, reaching -65 kPa, was distributed across almost the entire treated zone with PVD. This observation underscores the effectiveness of the ground improvement method.

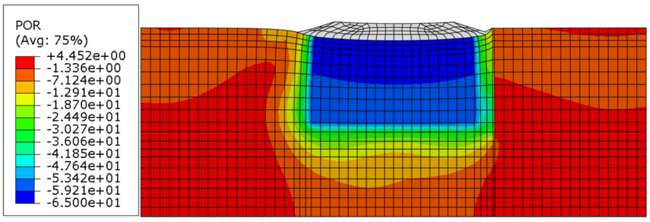

Fig. 8. Pore pressure distribution after treatment.

Supporting the effectiveness of the sheet pile wall, Figures 9 and 10 illustrate the distribution of vertical effective stress before and after treatment. Notably, the right side exhibits minimal variation in vertical stress, particularly near the ground surface, in comparison to the left side. This evidence strongly suggests that the sheet pile wall on the right side of the embankment efficiently shields against the transfer of stress from the construction site to the adjacent zone.

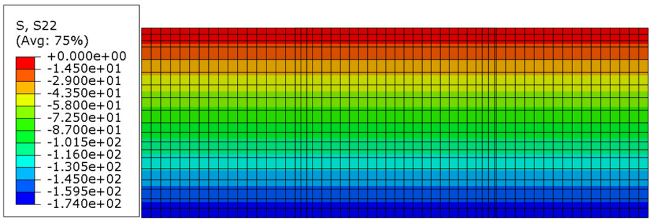

Fig. 9. Vertical effective stress before treatment.

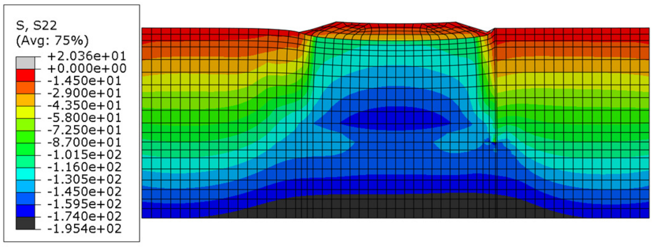

Fig. 10. Vertical effective stress after treatment.

The sheet pile wall serves as an effective barrier, successfully mitigating the distribution of both pore pressure and vertical stress. Consequently, the prevention of vertical and lateral displacements is evident, as illustrated in Figures 11 and 12. Figure 12 indicates a common tendency of lateral displacement to move inward toward the embankment on both the right and left sides. Notably, the right side, particularly at the embankment toe where the sheet pile is located, exhibits significantly less displacement than the left side.

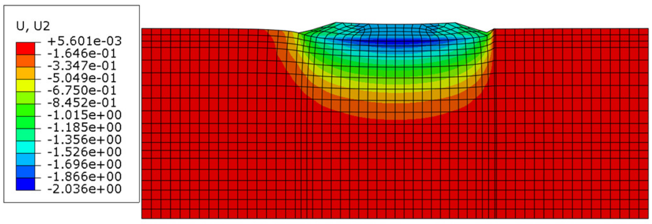

Fig. 11. Vertical displacements of the embankment.

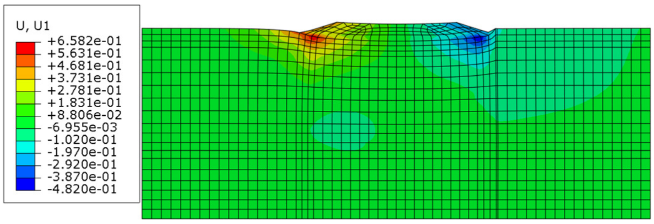

Fig. 12. Lateral displacements of the embankment.

VI. CONCLUSION

The comprehensive analysis and simulations conducted in this study provide valuable insights into the effectiveness of the ground improvement methods, particularly the implementation of sheet pile walls in combination with Prefabricated Vertical Drains (PVD) and vacuum consolidation. The following conclusions can be drawn from the results of this study:

- The sheet pile wall effectively obstructs negative pore pressure, contributing to the success of the ground improvement method.
- The sheet pile wall efficiently shields against stress transfer, resulting in minimal variations in vertical stress.
- The sheet pile wall serves as a barrier, successfully mitigating both pore pressure and vertical stress distributions, leading to the prevention of vertical and lateral displacements for the adjacent zone.

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