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A STUDY ON SETTLEMENTS OF ROAD EMBANKMENTS ON SOFT GROUND USING VERTICAL DRAINS

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Abstract. In civil engineering, the study of embankment settlement on soft ground is a vital geotechnical task in order to maintain serviceability of the road embankment, pavement, and facilities. This paper presents a study on settlements of road embankment on soft ground using vertical drains, including prefabricated-vertical drain (PVD), sand drain (SD), and sand compaction pile (SCP) on a number of packages of Hanoi – Haiphong Expressway Construction Project. The effectiveness of settlement prediction of vertical drain solutions is evaluated considering the ratios between the observed consolidation settlements and settlements predicted in the Detailed Design, in relation to the thickness of soft soil and the depth of treatment. Regression analysis is used to establish the correlation between the observed settlement and the height of embankment. The results show that (i) the design generally overestimated settlements; (ii) the ratios between observed and predicted settlements tend to positively correlate with the thickness of soft soil and the depth of treatment, and (iii) there are positive correlations between the height of embankment and the observed settlement. These correlations can be a valuable source of reference for anticipating settlements in basic design of highway projects with soft ground treated by vertical drains, in the regions that have geological stratum similar to Thabinh and Haihung formations of Bacbo Plain.

Keywords: settlement, ground treatment, embankment, soft soil, vertical drain.

1. INTRODUCTION

The primary concerns when constructing a road on soft ground are instability and excessive settlement of the road embankment, which would result in subsequent problems. In particular, excessive residual settlement cause pavement rutting, poor riding quality and hazardous damages to structures due to differential displacement. As a result, study of embankment settlement on soft ground is a vital geotechnical task in order to maintain serviceability of the road embankment, pavement, and facilities [1].

Specific significances of the settlement studies include: (i) to provide better understanding of the settlement behaviors during and after the construction of the road embankment; (ii) to anticipate the total settlement, on that basis to determine the consolidation degree and the removal conditions of surcharges before the pavement structure construction; and (iii) to estimate the additional earthwork quantity relating to the measurement and payment in the contracts. For these purposes, ability to predict the total settlement via establishing the relationship between the design (predicted) and the actual (observed) settlement is of great importance.

So far, many research works have been made to study the settlement behaviors under the road embankment and to investigate the relationship between the anticipated settlement data from the design and the actual data collected in the fields [1-3]. Rezania, Bagheri, Nezhad, and Sivasithamparam in [4] employed an anisotropic creep constitutive model known as Creep-SCLAY1S to study the installation effects of prefabricated vertical drains (PVDs) on the behavior of a full scale test embankment at Haarajoki embankment in Finland. A constitutive model was used to incorporate the effects of fabric anisotropy, structure and time. The numerical predictions were compared with field measurements and the results indicated that the creep model provides an improved approximation of field settlements; Ramli, Hossein, Puspanathan, and See-Sew in [5] conducted a case study in Tapin, South Kalimantan where two trial embankment sections were constructed using backfill materials transported from off-sites and from the local materials respectively. The result showed that the settlement under the embankment using the usual backfill material was bigger than the one with the combination of the local soil; in [6] a numerical modeling of the responses of Ballina test embankment was performed using an improved EVP-SANICLAY constitutive model with a novel rotational hardening (RH) law. The elasto-viscoplastic anisotropic constitutive model was implemented in PLAXIS to carry out the simulations of the case study embankment. The numerical modelled time-dependent deformations and pore water pressures during and after the embankment construction were compared with site measurements. The results showed that the model was capable of capturing the temporal changes in surface settlement and lateral deformations with good accuracy; in [7] two test embankments were built on an organic clay at the Lampen test site in Sweden where movements and pore pressures were measured for six years. Two- dimensional (2D) and one-dimensional 1D constitutive models were used to predict the settlement and pore pressures. The prediction results showed that the 2D model agreed relatively well with the measured total settlements and with pore pressures at different depths. A comparison between the predictions and the measured settlements and pore pressures showed that it is critical to study the trend over time and at different depth. It was concluded that creep should be included to provide better agreement with the in-situ settlements and pore pressures.

Other studies on settlement behavior and the comparison between the in-situ measured and numerically simulated settlements of test embankments can be found in [8-13]. Despite the fact that much effort has been made into comparing predicted and observed settlement, little has been known about the study on relationships between the aforementioned settlements and the thickness of soft soil and treatment depth, as well as the correlations between observed settlement and embankment height for various treatment solutions.

This paper presents the results of study on settlements of road embankments on soft ground using vertical drains from a number of packages of HaNoi – HaiPhong Expressway Construction Project. The actual consolidation settlements recorded from Surface Settlement Plates (SSPs) installed at the center of embankment were used to compare to settlements predicted in Detailed Design (DD), and to develop empirical connections with the embankment height that can be applied to estimate settlements in the basic design for highway projects with similar strata structure.

The research methodology: consolidation settlement of soft ground under the road embankment is influenced by a considerable number of factors, among which the height of the embankment and the geological condition are crucial. However, since during the basic design the detailed geological data such as physical-mechanical soil properties are typically not available but the overall strata structure, and the geological stratum in the study section does not change radically (see the Project Overview section below), this research attempts to establish relationships between the heights of embankment and the observed settlements using linear regression methodology. Data used for the regression analysis include the embankment heights in the detailed design and the associated consolidation settlements for each of the treatment methods (PVD, SD, and SCP) in the studied packages (EX-5 to EX-8). The comparison, however, does not include sections with significant changes in design, or where data is not sufficient to conduct an analysis.

The research significances: this settlement study aims to gain better understanding of the settlements of road embankments on soft ground using vertical drains, to rationalize the reasons behind the overestimation of the predicted settlement identified in the study, and to establish the correlations between the observed settlements and the heights of embankment. These established relationships can be used as a reference for anticipating settlements in basic design of highway projects with soft soil treated by vertical drains, in regions with geological stratum similar to ThaiBinh and HaiHung formations of BacBo Plain in Vietnam.

2. THE PROJECT OVERVIEW

Hanoi – Haiphong expressway is among the most significant expressway construction projects in Vietnam. The Project transverses HaNoi, HungYen, HaiDuong, and HaiPhong provinces with the total length of 105.50 km. The project is divided into ten packages [14], among which the study area covers 4 packages, including EX-5 (km48 - km63+300), EX-6 (km63+300 - km72), EX-7 (km72 - km81+300), and EX-8 (km81+300-km91+300). The total investment capital is approximately US$ 2 billion.

The Project passes through a geologically challenging region, with nearly 85% of its length is on soft ground. The geological treatment profile is essentially divided into four zones: A, B, C, and D (Figure 1). In the provinces of HaNoi and HungYen, the soft soil depth is typically 10–20 meters, whereas in HaiDuong and HaiPhong, the depth rises to 20–30 meters [15].

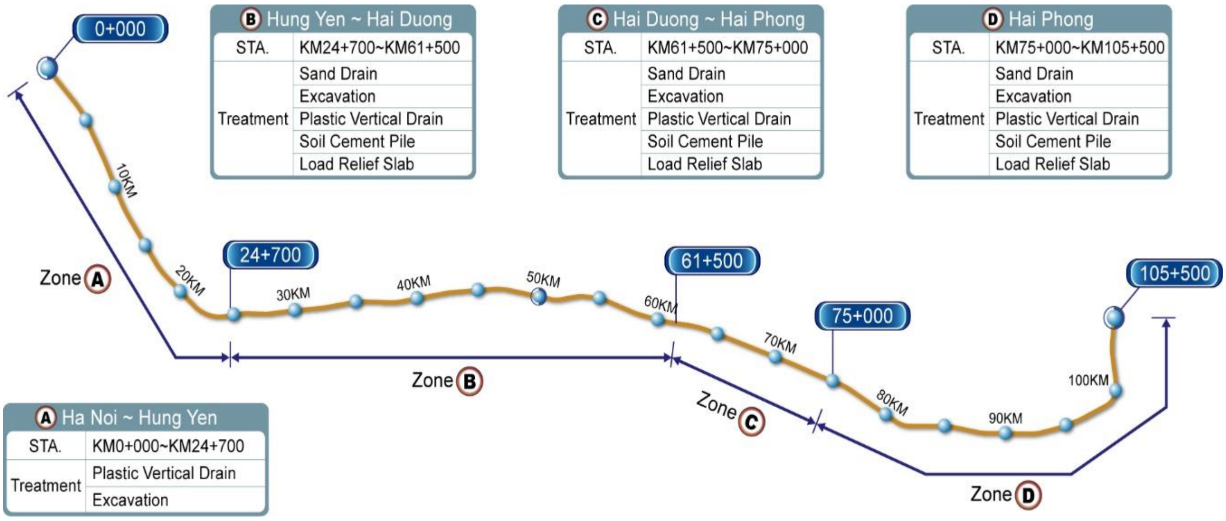
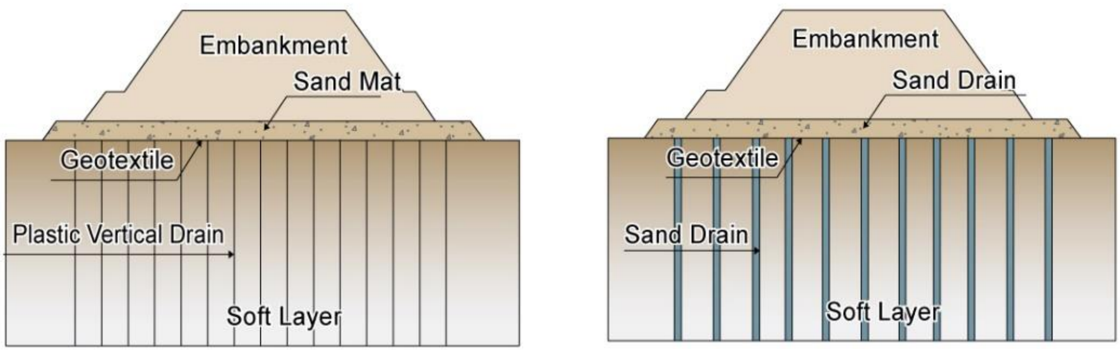


Figure 1. Sketch of soft soil treatment sections of Hanoi - Haiphong Expressway Project. Source [16].

Along the alignment, there are a variety of geological strata, including fluvial sediments, fluvial-marshy sediments, marine sediments, and fluvial-marine sediments [16]. The geological formation in Haiphong is comparable to those in the provinces of ThaiBinh and HaiHung in the BacBo Plain, according to a study of the city's geological map and the findings of a soil survey. In the highway corridor, the geological strata vary considerably and get more complex as the road transverses toward the East Sea. For instance, the geological stratum in HaiPhong city for packages close to the sea (EX-9, EX-10) is primarily composed of fluvial-marshy sediments, consisting of chocolate clay interbedded with black clay bearing plant debris and thin seams of peat, whereas the geological stratum in the Southern East of HaiPhong city and HaiDuong Province (packages EX-5 to EX-8) is primarily composed of fluvial-marine, consisting of three layers:

- Layer 1: Grey silty clay mixed with some fine-grained sand; 10m thick.
- Layer 2: Grey clayey silt mixed with some sand, muscovite scale and plant debris; 5m thick.
- Layer 3: Yellow-brownish clayey silt mixed with fine sand, muscovite scale and plant debris; 2m thick [15].



a) PVD b) SD/ SCP

Figure 2. Layout of vertical drain treatment methods.

A wide range of soft soil treatment solutions has been investigated and implemented in the Project, including soil removal and replacement, prefabricated vertical drain (PVD), sand drain (SD), sand compaction pile (SCP), deep-mixing method (DMM), and load-relief slab (pile-supported embankment). Although the Project has used a wide variety of soft soil treatment methods, the methods can be broadly divided into two groups: (i) consolidation acceleration (PVD, SD, SCP) and (ii) sliding prevention (deep mixing method, pile-supported embankments). The former is used extensively for conventional road embankments (Figure 2), in particular the SCP method is effective for both preventing slipping and accelerating consolidation, whereas the DMM and Pile methods are essentially applied for strict settlement control, such as bridge approaching sections [14].

This research focuses on studying settlement behaviours of the first group (consolidation acceleration) using vertical drains, including PVD, SD, and SCP. PVDs and SDs are commonly installed with a 0.9-1.5m centre-to-centre spacing in square or triangle configurations, whereas SCP comprises 70cm-diameter compaction sand columns. Table 1 [14, 17] provides specific information on the amounts of vertical drain treatment techniques included in the 4 packages.

Table 1. Quantities of vertical drain for soft soil treatment in various packages.

Item	Unit	EX5	EX6	EX7	EX8	SUM
PVD	m	3,126,240	9,803,356	7,996,463	1,181,490	22,107,549
SD	m	2,137,863	238,418	1,481,472	191,486	4,049,239
SCP	m	622,578	408,148	462,544	705,616	2,198,887

Geotechnical monitoring activities include: recording routinely at surface settlement plates (SSPs), horizontal alignment wood stakes, inclinometer, and piezometer. Three SSPs are distributed in a monitoring cross section, and five stakes for observation of horizontal displacement are distributed at 2.0m spacing. Monitoring cross sections are typically 100m apart [15,17]. The treatment of soft soils was followed by the construction of the embankment in accordance with the design. Depending on the construction schedule, some sections might need to wait until the soil has consolidated to a specified level before the surcharge is removed for construction of the pavement. Conditions for removal of surcharge are as follow:

- Consolidation level reaches at least 90%;
- Residual settlement (Δ_S) meets the Project's Specification ($\Delta_S \leq 10cm$ for bridge approaching sections; $\Delta_S \leq 20cm$ for culvert approaches, and $\Delta_S \leq 20cm$ for normal embankment sections;
- Factor of stability (k_S) complies with the Project's Specification: $k_S \geq 1.40$;
- The finished grade of the embankment at the surcharge removal must complies with the design elevation.

The Specification for Survey and Design of Road Embankment on Soft Soil TCCS 41: 2022/TCĐBVN [18] is established as a Project's applicable standard. The Asaoka method was used for prediction of settlements and evaluation of consolidation degree for its simplicity and reliability [14,19,20].

3. RESULTS AND DISCUSSIONS

3.1 Relationship between Observed Settlements and Predicted Settlements

3.1.1 Prefabricated Vertical Drain

Figure 3 depicts the relationship between observed settlement and settlement computed in the DD in connection to embankment height for package EX-7 using the PVD treatment method.

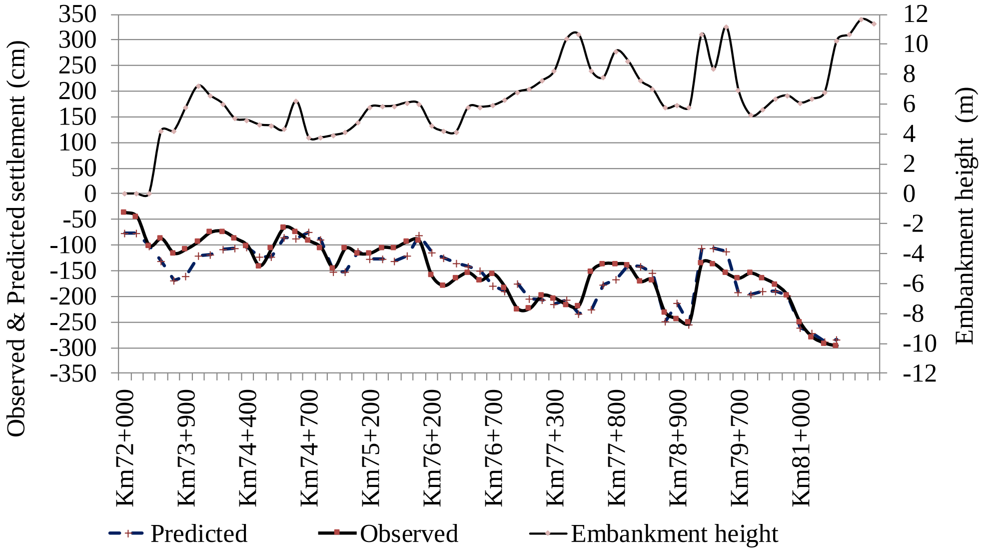


Figure 3. Observed settlements versus predicted settlements in EX-7, PVD method.

The ratios between observed settlements and predicted DD's settlements of the 4 packages is shown in Table 2.

Table 2. Ratios between observed settlements and predicted settlements, PVD method.

Package	EX-5	EX-6	EX-7	EX-8
Max	1.14	2.00	1.44	1.24
Min	0.45	0.24	0.47	0.54
Average	0.97	1.17	0.86	0.83

As can be seen in Figure 3, there are essentially comparable tendencies between the predicted and observed profiles, and there exists a significant number of segments where the predicted settlements are close to the observed settlements. However, in Package EX-7 there a number of sections the predicted data overestimate settlements, such as km72+400-km74+400, km75+000-km75+800, and km79+600-km80+800.

Table 2 further demonstrates that the average ratios are less than one, with the exception of Package EX-6. This shows that the settlements are often overestimated by the design. The reasons for this overestimation could be that the design input parameters remain constant for relatively long segments and tend to shift to the safety side, although the physical-mechanical properties vary considerably in reality, as explored from the database. Another reason could be that the settlement plates were not installed until after the vertical drains and sandmat layer were installed.

The thickness of the sandmat layer varies between 50cm and 140cm, thus the weight of the sandmat material and the load of construction equipment may cause some early settlement before the observed settlement is recorded. Despite that this phenomenon contributes to some of the differences between the two settlements, it has not been considered in the Detailed Design.

The data analysis shows that the thickness of soft soil and the depth of PVD treatment method increase noticeably from HungYen Province (EX-4) to EX-5 and EX-6 (ThanhHa, HaiDuong), and gradually decrease from EX-6 to EX-7 and EX-8. The ratios between observed and predicted settlements appear to be positively correlated with these variables. As the thickness of soft soil and the depth of treatment increases, so do the properties of the soil, and the challenges in the construction quality control. In contrast, due to design default assumptions such homogenous soil structure and excellent construction quality assurance, the design is frequently conservative with regard to these characteristics. But, in practice, the structure is usually imperfect, causing the ratio to rise as the depth of treatment and the thickness of soft soil increase.

3.1.2. Sand Drain

Figure 4 depicts the relationship between observed settlement and settlement computed (predicted) in the DD in relation to embankment height for package EX-7 using the SD treatment method.

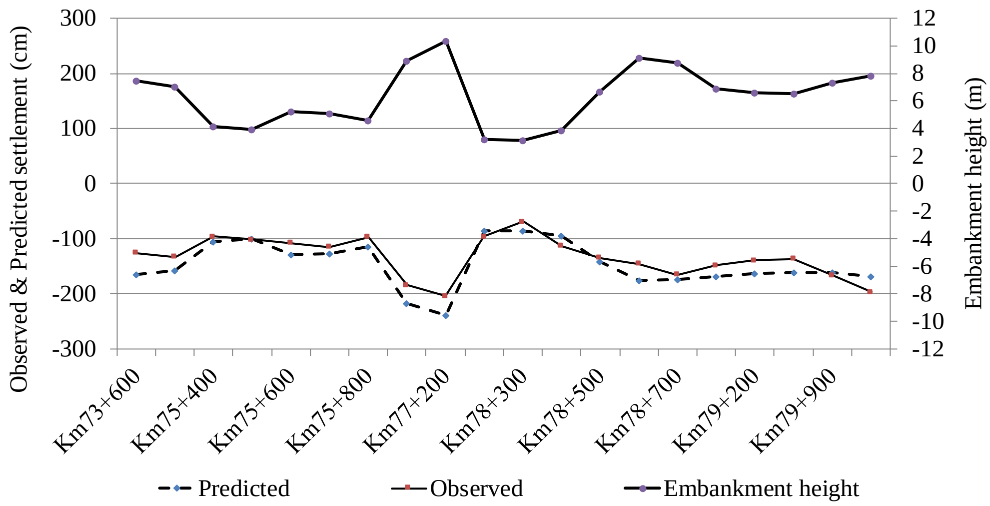


Figure 4. Observed settlements versus predicted settlements in EX-7, SD method.

The ratios between observed settlements and predicted settlements for SD method is summarised in Table 3. The table shows that except Package 5, the ratios between observed settlements and predicted DD's settlements are typically less than 1, demonstrating that the DD overestimates the settlement. Particularly, Package EX-6 significantly overestimates the settlement. Profiles in Figure 4 also support this overestimation.

Table 3. Ratios between observed settlements and predicted settlements by SD method.

Package	EX-5	EX-6	EX-7	EX-8
Max	1.07	0.83	1.18	1.30
Min	1.00	0.74	0.76	0.57
Average	1.02	0.80	0.92	0.95

According to database analyses, the ratios of observed to predicted settlements are positively correlated with the thickness of soft soil and the depth of treatment: from HungYen province (EX-4) to the maximum depth in EX-5, the minimum in EX-6, and then slightly increasing from EX-6 to EX-7 to EX-8. For the causes for the overestimation of settlements in the DD and the positive correlation between the ratio and the thickness of the soft soil as well as the depth of treatment, please refer to the remarks in Section 3.1.1.

3.1.3. Sand Compaction Pile

Figure 5 depicts the relationship between observed settlement and settlement predicted in the DD in relation to embankment height for package EX-6 using the SCP treatment method. The graph demonstrates that, in general, the predicted settlements exceed the observed settlements, in particular in Section km 63+550 to km 68+640.

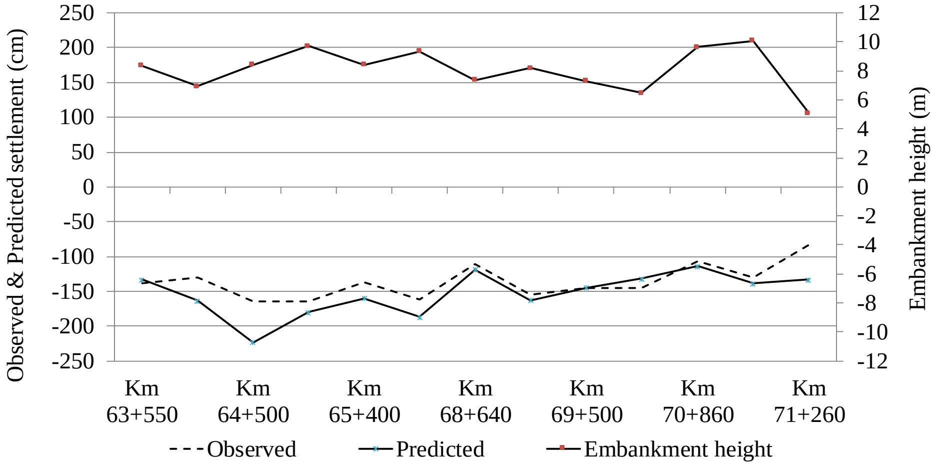


Figure 5. Observed settlements versus predicted settlements in EX-6, SCP method.

The ratios between observed settlements and predicted settlements for SCP method are shown in Table 4. With the exception of Package EX-5, it can be inferred from the profiles and statistics in Table 4 that all other packages significantly overestimate the settlement.

Table 4. Ratios between observed settlements and predicted settlements, SCP method.

Package	EX-05	EX-06	EX-07	EX-08
Max	1.65	1.11	1.47	1.30
Min	1.03	0.62	0.62	0.45
Average	1.14	0.90	0.84	0.73

The ratios of the observed and predicted settlements seem to be positively correlated with the depth of treatment and the thickness of the soft soil in general: According to database analyses, the depth of SCP treatment method and the thickness of soft soil increase from HungYen province (in EX-4) to the highest values in EX-5, after which they continuously decrease from EX-6 to EX-7 to EX-8.

Please refer to the remarks in Section 3.1.1 for the explanations of the overestimation of settlements in the DD and the positive correlation between the ratio and the depth of treatment as well as the thickness of the soft soil.

3.2 Relationship between Height of Embankment and Observed Settlement

A correlation between embankment height (thickness) and observed settlement can be established for all PVD, SD, and SCP treatment methods, using aggregated data from 4 packages (EX5 to EX-8). Specifically, the total treatment quantities were approximately 22 million metre of PVD, 4 million (m) of SD, and 2.2 million (m) of SCP (see Table 1).

3.2.1. PVD method

The relationship between the height (thickness) of the embankment and observed (actual) settlement of 4 packages (EX5 to EX-8) is shown in Figure 6.

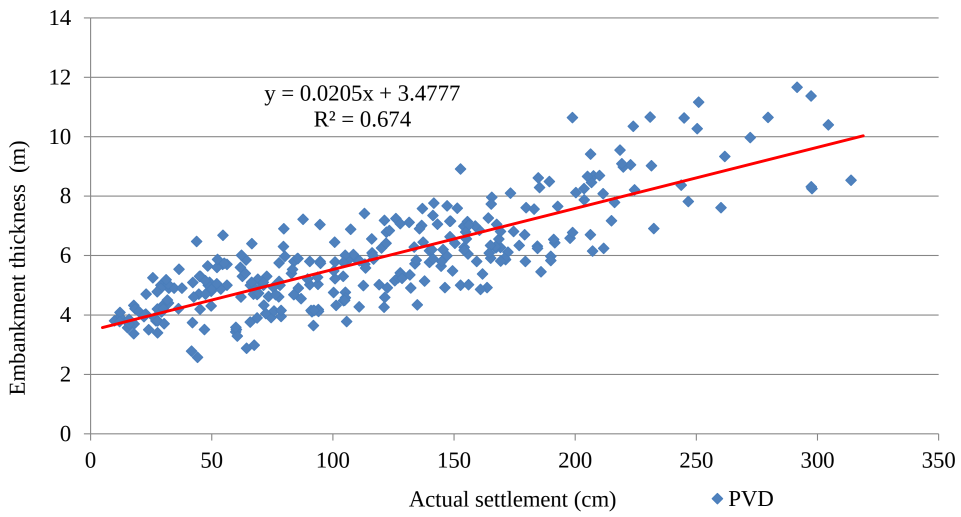


Figure 6. Relationship between the height of embankment and observed settlement, PVD method.

The embankment height for the PVD treatment method ranges from 2.57 to 11.60m, and the observed settlement is between 9.90 and 313.90cm (average 117.50cm). With a coefficient of determination (R^2) of 0.674, the relationship between embankment height and observed settlement is given by y=0.025x+3.4777, where x stands for observed settlement (cm) and y for embankment height (m).

3.2.2. SD method

Figure 7 depicts the link between the embankment height and observed settlement of the four packages using the SD method.

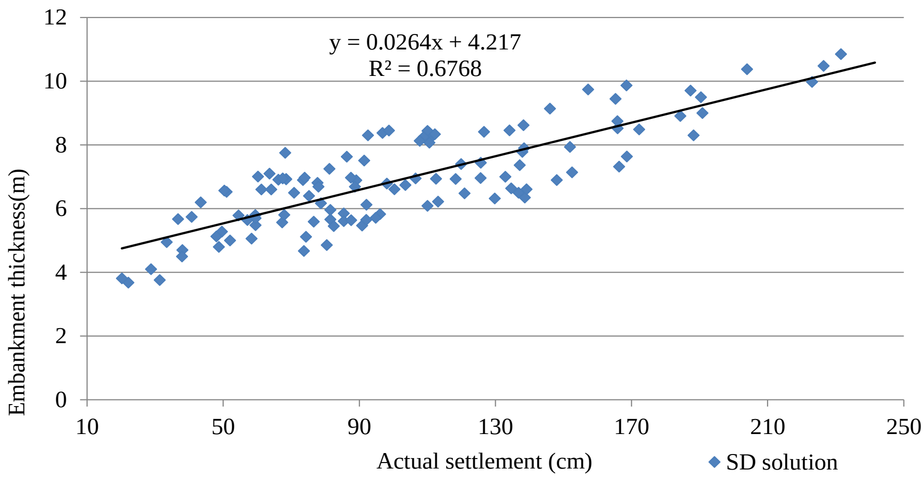


Figure 7. Relationship between the height of embankment and observed settlement, SD method.

The SD treatment method has an embankment height of 2.65m to 10.97m (average 6.65m), and a settlement of 20.20cm to 231.50cm cm (average 103 cm). The link between embankment height and observed settlement is represented by the Equation y = 0.0264x+4.217, where x stands for observed settlement (cm) and y stands for embankment height (m). This relationship has a coefficient of determination (R^2) of 0.6768.

3.2.3. SCP method

Figure 8 depicts the link between embankment height and observed settlement, which corresponds to the depth of treatment of six packages using the SCP method.

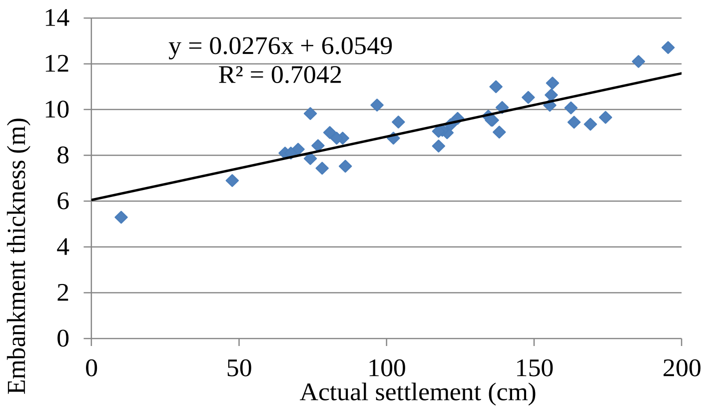


Figure 8. Relationship between the height of embankment and observed settlement, SCP method.

The height of the embankment ranges from 4.25m to 12.71m (average 8.95m), while the settlement with the SCP treatment method ranges from 10.10cm to 195.40cm (average 118,28cm). With a coefficient of determination (R2) of 0.7042, the relationship between embankment height and observed settlement is given by y = 0.0276x+6.0549, where x stands for observed settlement (in cm) and y for embankment height (m). The value of the determination coefficient indicates that the model replicates the observed outcomes relatively well. This relationship can be used as a reference for upcoming designs.

Discussions: This section provides a regression analysis that investigates the correlation between the embankment heights and the observed settlements for all vertical drain treatment methods, using aggregated data from 4 packages with large quantities (see Table 1). The results show that since both the variables move in the same direction, a positive correlation exists: as the embankment height increases, the settlement also increases, and via versus. The values of the determination coefficient (R2 = 0.6740 ÷ 0.7042) indicates that although the relationship between the embankment height and the observed settlement is far from perfect correlation, it is relatively strong. In other words, the model replicates the observed outcomes relatively well, with the intuitive coefficient of determination. This relationship can be used as a statistical reference to estimate the consolidation settlement in basic design for upcoming projects, given the known embankment height.

3. CONCLUSIONS

This paper presents results on an investigation of settlement road embankments on soft ground using vertical drains for packages EX-5 to EX-8 of Hanoi – HaiPhong Expressway. The ratios between the observed consolidation settlements at the embankment's centre and the settlements predicted in the Detailed Design (DD), in relation to soft soil thickness and treatment depth, are used to assess the effectiveness of vertical drain settlement prediction. To determine the relationship between the observed settlement and the height of the embankment, regression analysis is utilized.

The analysis's findings show that, in terms of settlement profiles' tendency, the DD design often overestimates settlements, with a few outliers. This overestimation may be attributed to a number of reasons: (i) the choice of design values tends to shift toward the safety side; (ii) the Surface Settlement Plates (SSPs) installation was put off until the sandmat layer and vertical drains were finished; and (iii) the sandmat layer material and the load of the construction equipment may cause some early settlement before the data on SSPs were initially gathered, but this phenomenon was not taken into consideration in the DD.

In investigating the relationship between the embankment height and observed settlement, the results show a relatively strong positive correlation with values of the determination coefficient (R2) in the range 0.6740 ÷ 0.7042. This indicates that the model replicates the observed outcomes relatively well, with the intuitive coefficient of determination. In areas with geological strata comparable to those of the BacBo Plain, these empirical connections can be applied to estimate settlements in the basic design for highway projects treated with vertical drains.

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