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# ROADWAY SETTLEMENT CHARACTERISTICS ON MEKONG DELTA FOR VARIOUS LANDFORMS

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**ABSTRACT:** The road network in the Mekong Delta faces challenges due to its low-lying topography and extensive layers of soft clay. These deposits, reaching depths of up to 25 m, are found in backswamp/swamp, sand dune, and mangrove marsh landforms. These soils generally have low total unit weight, high water content, and high compressibility. They are problems for road construction, and soft ground treatment must be applied. This study utilized data from 53 boreholes to assess the consolidation characteristics of each landform. According to the typical highway embankment construction, the primary consolidation showed the highway settlement in the ranges 186–1,174 mm, 107–1,049 mm, and 537–1,364 mm for the backswamp/swamp, sand dune, and mangrove marsh, landforms, respectively. These settlements exceed the maximum level of 250 mm for allowable settlement at 5 years post-construction. To address this issue, the prefabricated vertical drain (PVD) method is proposed as a solution to expedite settlement. PVDs, designed with 12–14 m, 10–12 m, and 14–16 m for the backswamp/swamp, sand dune, and mangrove marsh landforms, respectively, and a spacing of 1 m, accelerated the consolidation process, resulting in consolidation percentages of 87–92% within a notably shortened timeframe of 3 months through preloading. Upon completion of the preloading period, the remaining settlement ranges were 54–130 mm, 27–83 mm, and 67–170 mm for the backswamp/swamp, sand dune, and mangrove marsh landforms, respectively, which are all within the permissible limit (250 mm). These findings are important, as they offer valuable insights for the future planning, preliminary design, and construction of highway embankments, emphasizing the importance of incorporating PVDs as an effective measure in mitigating settlement issues.

*Keywords: Landform, Settlement, Highway Embankment, Soil Improvement*

## 1. INTRODUCTION

The Mekong Delta, one of the largest deltas in Asia, encompasses 12 provinces and is home to 18 million people. This region is undergoing continuous infrastructure development, with several major cities and significant potential for agricultural and industrial economies. As part of the Mekong Delta Regional Master Plan for 2021–2030, extensive infrastructure projects are planned, including highways, national roads, airports, seaports, passenger port clusters, and inland waterway cargo ports [1]. Therefore, comprehensive knowledge of the geotechnical properties of the soft soil in the area is crucial for the future planning and design of these infrastructure projects.

Notably, the settlement of soft clay layers poses a significant challenge in the Mekong Delta. The delta consists of young sedimentary deposits, formed 6,000–8,000 years ago through the accretion of the Mekong River, influenced by sea activities [1]. Previous study [1, 2] have highlighted the high compressibility of soft clay in the region, and the impact of the silt and clay content on permeability and settlement time. Therefore, the literature has emphasized the need for soil improvement techniques due to the critical compressibility of soft clay.

Various techniques for improving highway embankments in the Mekong Delta have been explored, including soil cement stabilization, sand compaction piles, and soil cement columns [3, 4]. However, prefabricated vertical drains (PVDs) have gained prominence due to their cost-effectiveness, swift installation, and environmental safety [5-7]. Initial PVD research focused on enhancing soft clay conditions in southern Vietnam, followed by performance evaluation, model testing, and numerical modeling [5-7]. PVDs also find applications beyond Vietnam, such as settlement studies in Istanbul, Turkey, and optimal design for soft ground in China [8, 9]. These global cases highlight the broad significance and potential of PVDs for ground improvement.

The road network in the Mekong Delta faces various challenges due to its low-lying topography, extensive hydrographic network, and thick Holocene deposits with diverse sediment origins [2]. These deposits have produced different landforms, primarily very soft to soft clay near the ground surface. The thickness and properties of the soft soil vary significantly across these landforms, making them critical factors to consider during road construction [1, 2].

The current paper studied the consolidation settlement characteristics of soft clay as follows: 1) estimate the primary consolidation settlement of highway embankments related to landforms; 2) identify settlement that exceeds the allowable settlement within 5 years post-construction; and 3) suggest the preliminary design of highway embankments and their improvement using PVDs in soft ground.

## 2. RESEARCH SIGNIFICANCE

By 2030, the Mekong Delta will have undergone significant development, including the construction of highways and national roads. The current study provides crucial information for highway planning and estimating road embankment settlement on different landforms in the delta region. In addition, engineers can use the developed information to estimate road embankment settlement. This preliminary information indicates the roadway settlement characteristic for various Mekong landforms and provides guidelines for selecting road improvement techniques that can be applied cost-effectively.

## 3. GEOLOGICAL CONDITIONS

The Mekong Delta (Fig.1) is a triangular region bordered by Phnom Penh, Cambodia, the mouth of the Saigon River in Ho Chi Minh City, Vietnam, and Ca Mau Cape in the south of the Ca Mau Peninsula, Vietnam. The Delta covers an estimated area ranging from 62,520 km$^2$ to 93,781 km$^2$ [1]. Based on the results of a previous study [1], has described the detailed characteristics of the landforms in the area. The upper Delta plain predominantly comprises backswamp and swamp environments (Fig.1), occupying low-lying and wet flood basins. The lower Delta plain has northeast-to-southwest trending sand dune (Fig.1). The Ca Mau Peninsula features extensive mangrove marshes and forests in its low-lying areas.

The Mekong Delta, located in the downstream region of the Mekong River, significantly affects the flood regime that may lead to geotechnical failure mechanisms in road infrastructure. These include wave overtopping, flood overflowing, and road slope cover because the irrigation system is complicated, with rivers, secondary irrigation, navigation channels, and canals [10]. In addition, roads are frequently flooded during the rainy season, with only the route linking provinces being paved.

## 4. METHODOLOGY

### 4.1 Data Collection

Data collection of geological and geotechnical engineering properties comprised two secondary sources: 1): Construction Laboratory No. LAS-XD 1078, No. LAS-XD 1584, and No. LAS-XD 451 in Vietnam; and 2) academic publications, such as journals and proceedings [1, 11].

Specific criteria, including a coordinate reference system and detailed soil stratigraphy, guided borehole selection (reflecting landform sediments' behavior).

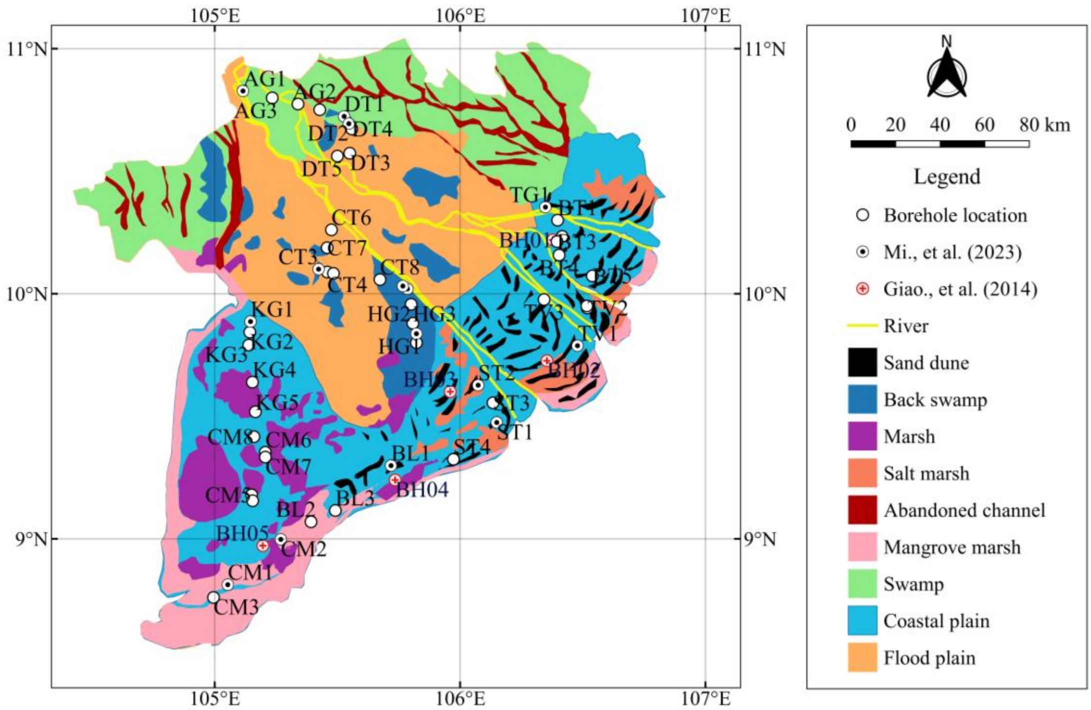



Fig.1 Distribution of landforms in Mekong Delta (modified from [1]).

### 4.2 Data Processing

The data processing stage involved data validation, screening, and statistical analysis following the approach proposed by [1]. In total, 53 boreholes were included in this research. Statistical analysis was performed using a confidence interval of 95% and a limit of two standard deviations (Mean $\pm$ 2SD). Additionally, properties such as compression index, recompression index, and overconsolidation ratio were estimated using correlation equations proposed by [12].

### 4.3 Data Analysis

*4.3.1 Primary consolidation settlement*

The primary consolidation settlements were computed following the classical theory outlined by Terzaghi [13]. Eq. (1) for normally consolidated clays, in overconsolidated clays, Eq. (2) was applied for $\sigma'_{v0} + \Delta\sigma'_v \le \sigma'_c$ and Eq. (3) for $\sigma'_{v0} + \Delta\sigma'_v > \sigma'_c$:

$$S_c = \frac{C_c \times H}{1+e_0} \log\left(\frac{\sigma'_{v0}+\Delta\sigma'_v}{\sigma'_{v0}}\right) \quad (1)$$

$$S_c = \frac{C_r \times H}{1+e_0} \log\left(\frac{\sigma'_{v0}+\Delta\sigma'_v}{\sigma'_{v0}}\right) \quad (2)$$

$$S_c = \frac{C_r \times H}{1+e_0} \log\frac{\sigma'_c}{\sigma'_{v0}} + \frac{C_c \times H}{1+e_0} \log\left(\frac{\sigma'_{v0}+\Delta\sigma'_v}{\sigma'_c}\right) \quad (3)$$

where $S_c$ is primary consolidation (mm), $C_c$ is the compression index, $C_r$ is the recompression index, $H$ is the height of soft soil layer (m), $e_0$ is initial void ratio, $\sigma'_{v0}$ is the effective overburden pressure (t/m$^2$), $\Delta\sigma'_v$ is the embankment load pressure (t/m$^2$), and $\sigma'_c$ is the preconsolidation pressure (t/m$^2$).

Eq. (2) and (3) used $C_r = 0.1\ C_c$ (the same slope $e-\log(\sigma')$) based on the correlation between $C_c$ and $C_r$ from the raw data of the consolidation test (ASTM D2435 [14])

*4.3.2 Time rate consolidation*

The average degree of consolidation considering the rate of consolidation for clay soils was calculated using Eq. (4) [12]:

$$U = \frac{S_{(t)}}{S_c} \quad (4)$$

where $U$ is average degree of consolidation (%), $S_{(t)}$ (mm) is settlement at time t (month), and $S_c$ is final primary consolidation (long-term settlement).

*4.3.3 Consolidation using PVDs*

The average degree of consolidation, considering the vertical and horizontal consolidation effects, was proposed by Carrillo [15], as shown in Eq. (5):

$$U = 1-(1-U_v)(1-U_h) \quad (5)$$

where $U_v$ is the vertical degree of consolidation (%), and $U_h$ is the horizontal degree of consolidation (%). The current study utilized Barron's theory [16] to calculate consolidation by horizontal drainage.

## 5. SOIL PROPERTIES

The soft clay samples were collected from various provinces in Mekong Delta. Statistical analysis was conducted for each landform: backswamp/swamp (21 boreholes from An Giang, Dong Thap, Hau Giang Provinces and Can Tho City), sand dune (18 boreholes from Tien Giang, Ben Tre, Tra Vinh, Soc Trang, and Bac Lieu Provinces), and mangrove marsh (14 boreholes from Kien Giang and Ca Mau Provinces).

Table 1 Summary of statistical analysis of soft clay properties in each landform, Mekong Delta.

| Soil property | Statistical analysis | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Backswamp, swamp | | | Sand dune | | | Mangrove marsh | | |
| | Mean | SD | Mean $\pm$ 2SD | Mean | SD | Mean $\pm$ 2SD | Mean | SD | Mean $\pm$ 2SD |
| Thickness (m) | **13.84** | 2.26 | 9.33–18.36 | **8.89** | 3.76 | 1.37–16.41 | **14.59** | 5.31 | 3.96–25.22 |
| Clay (%) | **45.41** | 9.94 | 25.52–65.29 | **44.45** | 11.64 | 21.18–67.73 | **47.41** | 12.65 | 22.11–72.71 |
| Silt (%) | **38.76** | 12.23 | 14.29–63.22 | **39.49** | 7.61 | 24.27–54.71 | **34.21** | 11.32 | 11.57–56.84 |
| Sand (%) | **16.19** | 13.32 | 1.50–42.83 | **24.09** | 12.11 | 2.02–48.31 | **17.98** | 7.70 | 2.58–33.38 |
| $W_n$ (%) | **71.55** | 13.81 | 43.92–99.17 | **60.27** | 11.85 | 36.58–83.96 | **68.26** | 18.82 | 30.62–105.91 |
| LL (%) | **58.19** | 12.13 | 33.94–82.44 | **50.92** | 10.07 | 30.78–71.07 | **58.68** | 15.03 | 28.61–88.74 |
| PL (%) | **32.32** | 6.92 | 18.48–46.16 | **27.67** | 5.05 | 17.56–37.78 | **30.38** | 6.61 | 17.15–43.60 |
| PI (%) | **25.57** | 7.56 | 10.45–40.69 | **24.24** | 6.52 | 11.20–37.29 | **27.74** | 9.46 | 8.82–46.67 |
| $\gamma_t$ (t/m$^3$) | **1.55** | 0.07 | 1.42–1.69 | **1.62** | 0.09 | 1.43–1.80 | **1.56** | 0.10 | 1.36–1.77 |
| $e_0$ | **1.90** | 0.31 | 1.28–2.53 | **1.62** | 0.46 | 0.70–2.53 | **1.79** | 0.48 | 0.84–2.75 |
| $C_c$ | **0.41** | 0.09 | 0.22–0.59 | **0.31** | 0.09 | 0.12–0.49 | **0.41** | 0.12 | 0.17–0.65 |
| $C_r$ | **0.04** | 0.02 | 0.02–0.06 | **0.03** | 0.01 | 0.01–0.05 | **0.05** | 0.01 | 0.05–0.07 |
| CR | **0.15** | 0.02 | 0.11–0.19 | **0.11** | 0.03 | 0.06–0.17 | **0.16** | 0.02 | 0.12–0.20 |
| $C_v \times 10^{-3}$ (cm$^2$/s) (WC) | **0.80** | 0.14 | 0.51–1.08 | **0.94** | 0.23 | 0.49–1.39 | **0.63** | 0.08 | 0.47–0.79 |
| $C_v \times 10^{-3}$ (cm$^2$/s) (NC) | **0.21** | 0.02 | 0.17–0.25 | **0.25** | 0.03 | 0.20–0.30 | **0.20** | 0.03 | 0.15–0.26 |
| OCR | **4.69** | 2.26 | 0.16–9.22 | **2.88** | 1.07 | 0.75–5.02 | **1.36** | 0.57 | 0.22–2.50 |

*Note: Mean, the mean value, SD, Standard deviation, WC, Weathered clay, NC, Normally consolidated*

The mangrove marsh landform showed notable differences in soft clay properties (higher water content, plasticity index, and compression index), indicating increased compressibility.

## 6. SOIL STRATIGRAPHY

Generally, a soft ground structure can be divided based on the characteristics of landforms, the thickness of the soft clay, and the overconsolidation ratio of the soft clay.

### 6.1 Soil Profile

The soil profile for each landform was described based on the section shown in Fig.2, consisting of three main soil units:

The backswamp/swamp landform is shown in Fig.3 (1) The soil profile had very soft to soft clay from the surface to approximately -16.9 m, with a thickness ranging from 8 to 16.2 m. (2) Below the very soft to soft clay layer was a layer of stiff to very stiff clay interbedded with medium dense sand, extending from a depth of -8 m to -45 m. In Dong Thap Province (DT1 and DT2), the very soft clay layer was thinner due to sedimentation from the river belt. This landform was in a freshwater zone and experienced high flood levels during the rainy season. The predominant soft soil in this area consisted of alluvial soil and wetland deposits.

The typical soil profile in the sand dune is shown in Fig.4 (1) The upper layer is very soft to soft clay from the surface to about -23 m (with the thickness ranging from 2.5 m to 22 m). (2) Beneath the very soft to soft clay, there was a medium to stiff clay layer with intercalations of very loose to loose sand, stiff to very stiff clay, very stiff to hard clay, and medium dense sand at a depth of -4 m to -43 m. In Tra Vinh Province (TV0, TV1, TV2, and TV3), the soft clay thickness was relatively thinner (2.5–6 m) due to erosion, while some boreholes, such as BH01 and BH02, had a greater thickness (18–22 m) due to sediment re-deposition after erosion from the Mekong River and its branches.

The mangrove marsh landform had three main soil units, as shown in Fig.5 (1) First, there was a layer of very soft to soft clay ranging from the surface to approximately -26 m with a thickness of 6–25 m. Mangrove roots and longshore currents contributed to sediment accumulation. (2) Below the soft clay were medium to very stiff clays from 3 to 38 m depth. (3) Interbedded layers of medium to dense sand and stiff to very stiff clay was underlain by an upper soft to medium clay layer, transitioning into hard clay.

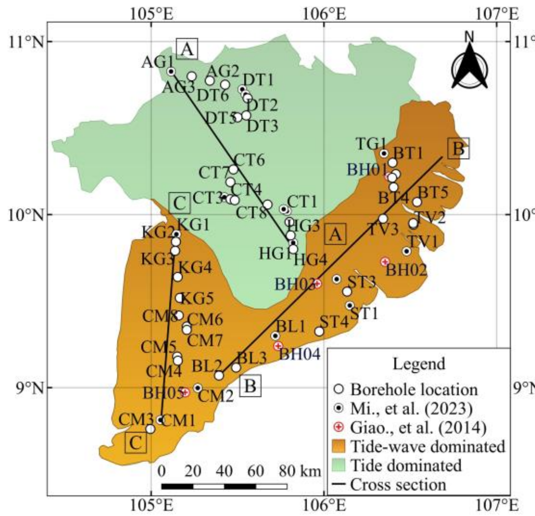



Fig.2 Borehole locations in Mekong Delta.

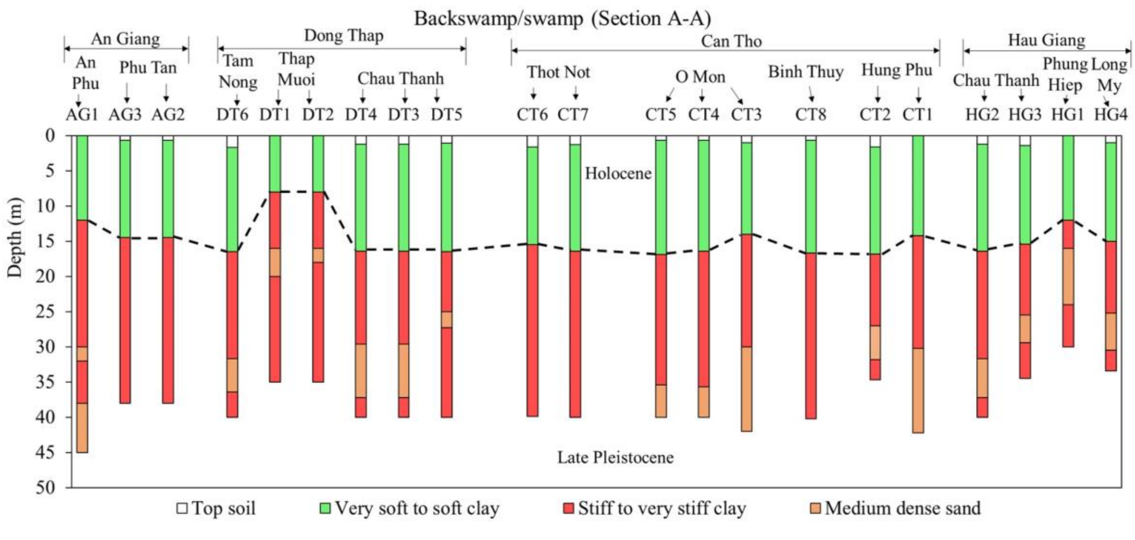



Fig.3 Soil profile of back swamp/swamp landform.

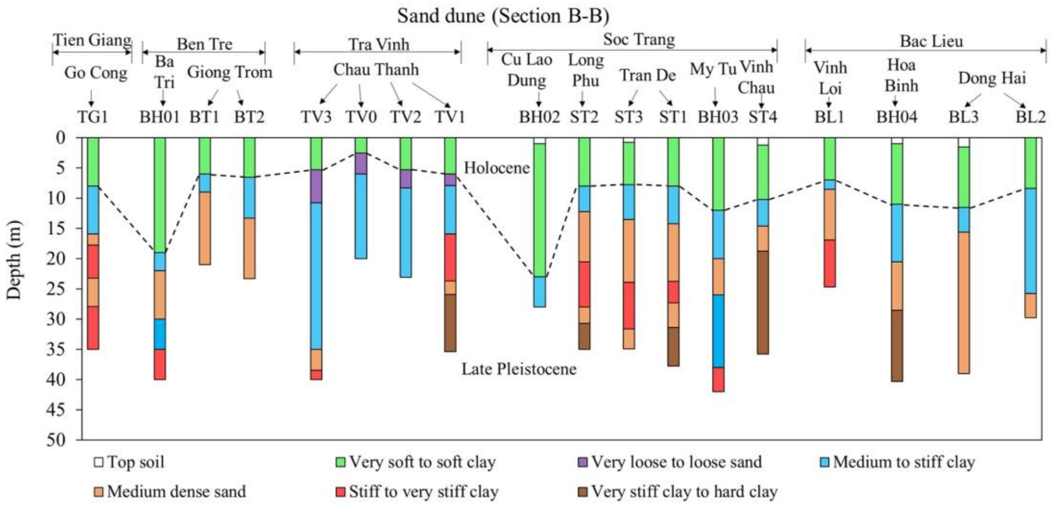



Fig.4 Soil profile of sand dune landform.

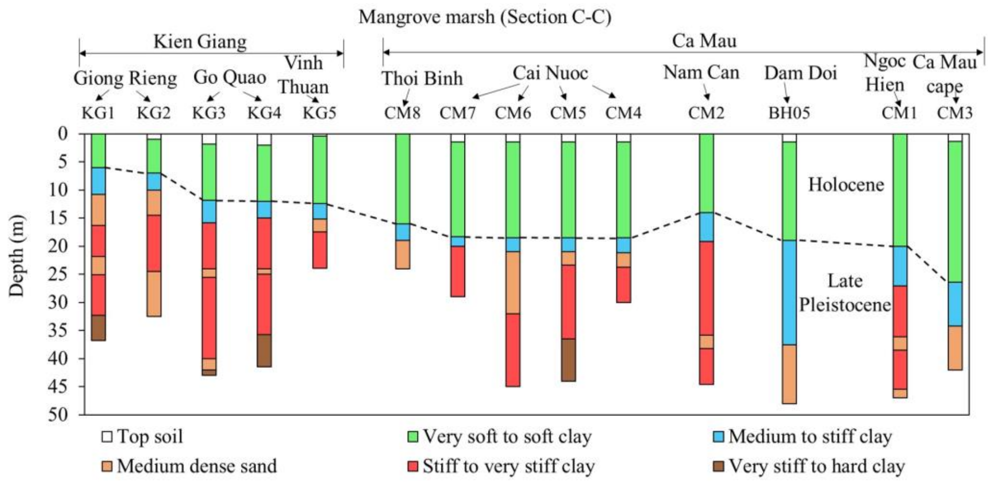



Fig.5 Soil profile of mangrove marsh landform.

## 6.2 Weathered Crust

The presence of a weathered crust, indicated by overconsolidation ratio (OCR), is an essential factor for settlement calculations. It indicates the weathered crust formed by the drying process of the sun.

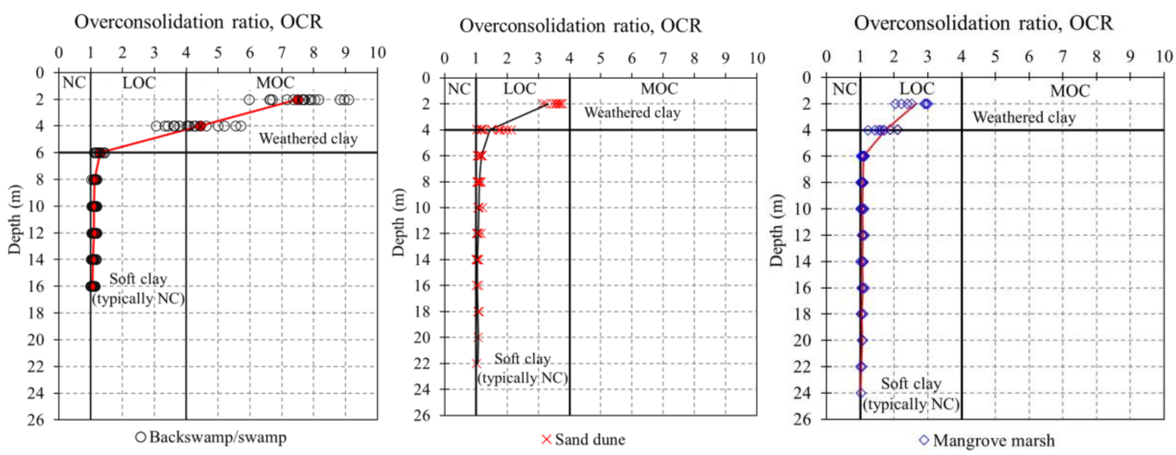



Fig.6 OCR versus depth of soft clay in Mekong Delta, classification by Kulhawy [17].

According to Fig.6, the highest OCR values were near the surface, gradually decreasing with depth. In the backswamp and swamp landform, the weathered crust was 6 m thick, with the top 4 m moderately overconsolidated (MOC). In the sand dune and mangrove marsh areas, the top crusts were 4–5 m thick, falling within the range of lightly overconsolidated (LOC) conditions. These weathered crust characteristics have a major impact on the geotechnical behavior and settlement of the soil profiles in each landform.

## 7. PRELIMINARY DESIGN CRITERIA

The preliminary design of highway embankment and soil improvement method is based on criteria established by relevant government organizations, as depicted in Fig.7 and Table 2. A sand blanket is utilized for consolidation drainage on the ground surface, with its typical side slopes being 1:1.5 on both sides. Preloading is achieved by placing a temporary surcharge on the soft ground before construction, such as earth fill or sandbags. The height of embankment above the natural ground surface is determined based on the flood level specific to each location in Mekong Delta. Methods such as PVDs are used to accelerate settlement in soft soil, considering the depth of soft clay layer in the three different landforms and economic considerations.

### 7.1 Typical Highway Embankment

The design of the highway embankment in each landform was calculated according to Vietnamese standards [18]. In addition, the height of the embankment (H = 3 m) was selected based on the flood situation (>2 m) in Mekong Delta [19].

### 7.2 Soil Improvement Using PVDs

PVDs are a practical choice for soil improvement when settlement exceeds the allowable limit. The length and spacing of PVDs are important design parameters, with a recommended total penetration length in soft clay [9]. Partial penetration is a cost-effective option for deep soft soil layers. The current study examined partially penetrated PVDs in each landform. In the backswamp and swamp areas, the PVD lengths ranged from 12 to 14 m, while in the mangrove marsh, lengths varied from 14 to 16 m, for sand dune with thinner, soft clay layers (except some boreholes having a great thickness (BH01 and BH02)). Therefore, the suitable length of the PVDs was approximately 10–12 m.

The PVDs drains were spaced at 1 m in a triangular pattern [20]. The horizontal permeability was three times higher than the vertical permeability, as proposed by Barron [16]. The dimension of the equivalent drain diameter followed the requirements of ASTM D5199 [21].

Table 2 Study of PVD improvements.

| Item | Unit | Value |
|---|---|---|
| PVD type | Flodrain (FD4-EX) | |
| PVD pattern | Triangular | |
| PVD spacing | m | 1 |
| Equivalent diameter of drain | mm | 66.24 |
| Hydraulic conductivity ratio, $k_h/k_s$ | | 3 |
| Length of PVDs on each landform | m | |
| a) Backswamp/swamp | m | 12–14 |
| b) Sand dune | m | 10–12 |
| c) Mangrove marsh | m | 14–16 |

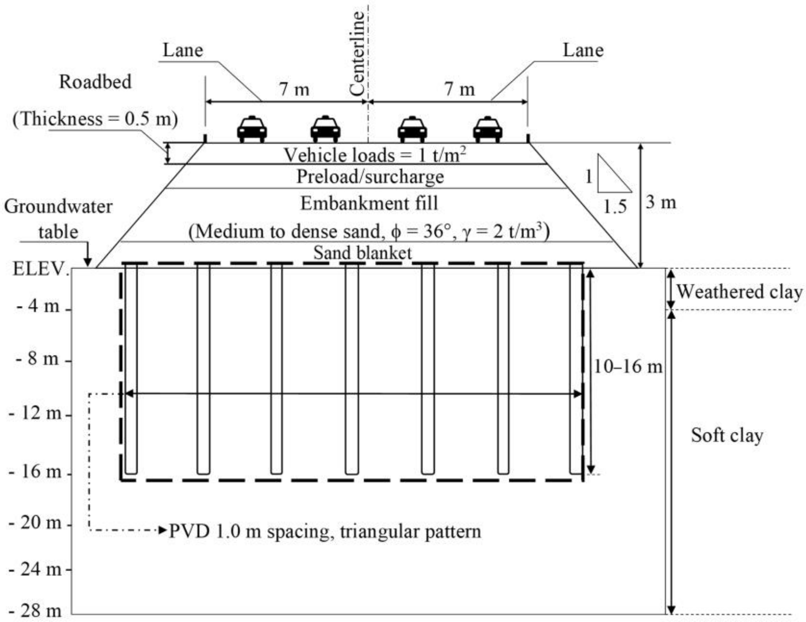


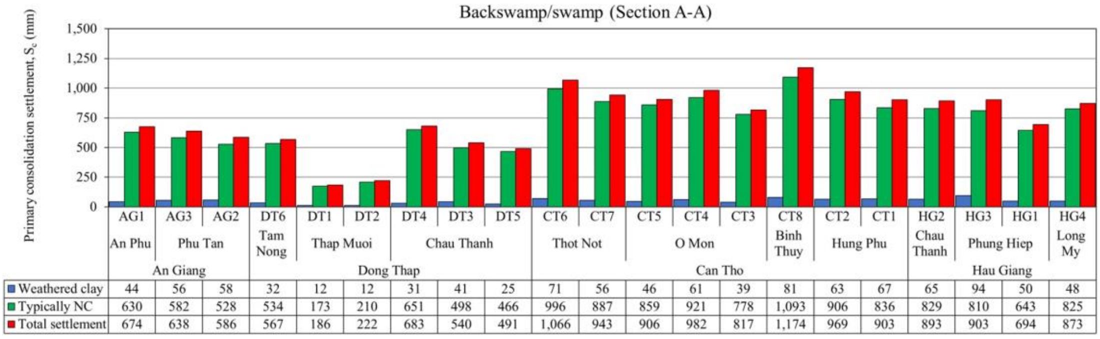

Fig.7 Design of highway embankment and PVDs.

## 8. RESULTS AND DISCUSSION

### 8.1 Primary Consolidation Settlement of Highway Embankment in Each Landform

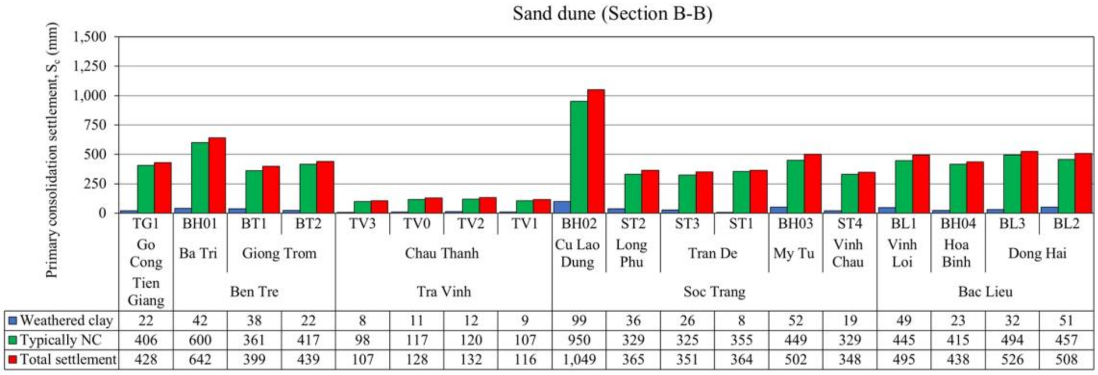
The primary consolidation settlements of weathered clay, soft clay (typically normally consolidated (typically NC)), and total settlement on each landform are shown in Figs. 8–10 and Table 3, with some comments and discussion below:

Generally, sand dune had the lowest consolidation levels among the three landforms, with total settlement in the range 107–1,049 mm. The settlement of weathered clay in this landform was in the range 8–99 mm. The coastal environment with sediment deposition from tides and wave action contributed to instability and the presence of thin sand layers. Backswamps/swamps had medium to high consolidation levels, with a total settlement range of 186–1,174 mm. The settlement of weathered clay in these areas was in the range 12–94 mm. Mangrove marshes had high consolidation levels, with the total settlement in the range 537–1,364 mm. The settlement of weathered clay in this landform was in the range 56–123 mm. These results highlighted the varying degrees of consolidation settlement and the influence of weathered clay in each landform.



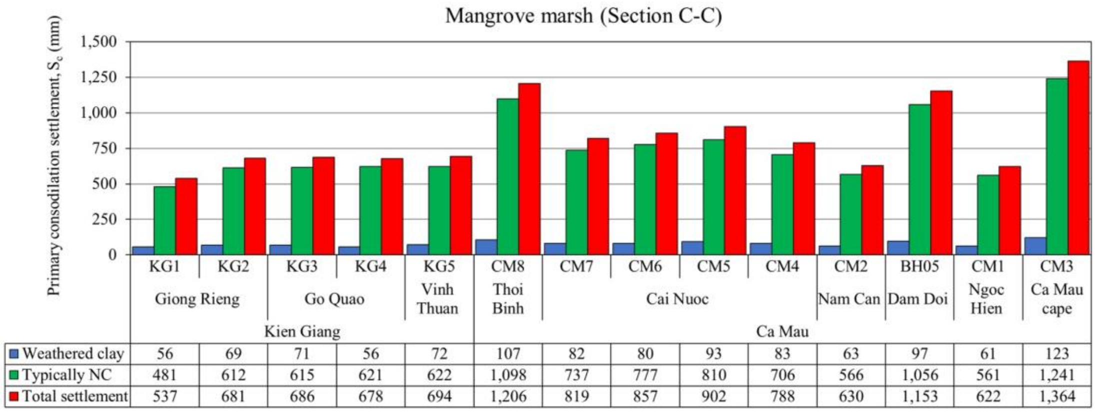

| | AG1 | AG3 | AG2 | DT6 | DT1 | DT2 | DT4 | DT3 | DT5 | CT6 | CT7 | CT5 | CT4 | CT3 | CT8 | CT2 | CT1 | HG2 | HG3 | HG1 | HG4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | An Phu | Phu Tan | | Tam Nong | Thap Muoi | | Chau Thanh | | | Thot Not | | O Mon | | | Binh Thuy | Hung Phu | | Chau Thanh | Phung Hiep | | Long My |
| Weathered clay | 44 | 56 | 58 | 32 | 12 | 12 | 31 | 41 | 25 | 71 | 56 | 46 | 61 | 39 | 81 | 63 | 67 | 65 | 94 | 50 | 48 |
| Typically NC | 630 | 582 | 528 | 534 | 173 | 210 | 651 | 498 | 466 | 996 | 887 | 859 | 921 | 778 | 1,093 | 906 | 836 | 829 | 810 | 643 | 825 |
| Total settlement | 674 | 638 | 586 | 567 | 186 | 222 | 683 | 540 | 491 | 1,066 | 943 | 906 | 982 | 817 | 1,174 | 969 | 903 | 893 | 903 | 694 | 873 |

Fig.8 Total consolidation settlement of soft clay (mm) in backswamp/swamp landform.




| | TG1 | BH01 | BT1 | BT2 | TV3 | TV0 | TV2 | TV1 | BH02 | ST2 | ST3 | ST1 | BH03 | ST4 | BL1 | BH04 | BL3 | BL2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Go Cong | Ba Tri | Giong Trom | | Chau Thanh | | | | Cu Lao Dung | Long Phu | Tran De | | My Tu | Vinh Chau | Vinh Loi | Hoa Binh | Dong Hai | |
| Weathered clay | 22 | 42 | 38 | 22 | 8 | 11 | 12 | 9 | 99 | 36 | 26 | 8 | 52 | 19 | 49 | 23 | 32 | 51 |
| Typically NC | 406 | 600 | 361 | 417 | 98 | 117 | 120 | 107 | 950 | 329 | 325 | 355 | 449 | 329 | 445 | 415 | 494 | 457 |
| Total settlement | 428 | 642 | 399 | 439 | 107 | 128 | 132 | 116 | 1,049 | 365 | 351 | 364 | 502 | 348 | 495 | 438 | 526 | 508 |

Fig.9 Total consolidation settlement of soft clay (mm) in sand dune landform.




| | KG1 | KG2 | KG3 | KG4 | KG5 | CM8 | CM7 | CM6 | CM5 | CM4 | CM2 | BH05 | CM1 | CM3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Giong Rieng | | Go Quao | | Vinh Thuan | Thoi Binh | Cai Nuoc | | | | Nam Can | Dam Doi | Ngoc Hien | Ca Mau cape |
| Weathered clay | 56 | 69 | 71 | 56 | 72 | 107 | 82 | 80 | 93 | 83 | 63 | 97 | 61 | 123 |
| Typically NC | 481 | 612 | 615 | 621 | 622 | 1,098 | 737 | 777 | 810 | 706 | 566 | 1,056 | 561 | 1,241 |
| Total settlement | 537 | 681 | 686 | 678 | 694 | 1,206 | 819 | 857 | 902 | 788 | 630 | 1,153 | 622 | 1,364 |

Fig.10 Total consolidation settlement of soft clay (mm) in mangrove marsh landform.

Table 3 Summary of total consolidation settlement of soft clay in each landform.

| Primary consolidation, $S_c$ $(mm)$ | Weathered clay | | | Typical NC | | | Total settlement | | |
|---|---|---|---|---|---|---|---|---|---|
| Landforms | Min. | Max. | Ave. | Min. | Max. | Ave. | Min. | Max. | Ave. |
| Backswamp/swamp | 12 | 94 | 50 | 173 | 1,093 | 698 | 186 | 1,174 | 748 |
| Sand dune | 8 | 99 | 31 | 98 | 950 | 376 | 107 | 1,049 | 408 |
| Mangrove marsh | 56 | 123 | 80 | 481 | 1,241 | 750 | 537 | 1,364 | 830 |

*Note: Min., Minimum; Max., Maximum; Ave., Average, typical NC, typical normally consolidated*

In the mangrove marsh landform, which is relatively young (formed 2,000 years ago), the progradation process has continued and widened the Delta, primarily southwestward according to the direction of the longshore wave. Consequently, this landform had a substantial deposition of soft clay compared to the other landforms, primarily influenced by the dominant longshore current and resulting in the soft clay layer in the mangrove marsh having the greatest thickness (Fig.5) and the highest water content ($W_n$ = 30.62–105.91%) and compression index ($C_c$= 0.17–0.65) among the three landforms.

The settlement contribution of weathered clay was relatively small, accounting for approximately 5–10% of the total settlement in all three landforms. In addition, the consolidation process of weathered clay was shorter during construction due to its shorter drainage path. The thickness of the weathered clay was about 2–6 m (Fig.6) in the three landforms. Furthermore, the vertical coefficient of consolidation ($C_v$) of weathered clay is higher than that of soft clay (typically NC), as shown in Table 2. Thus, the rate of settlement in the weathered clay was much faster than for the soft clay (typically NC). Settlement of the soft clay layer (typically NC) in embankments is a major concern in civil engineering.

### 8.2 Post Construction Settlement at 5 Years

According to Wong [22], the allowable 5 year post-construction settlement should be less than 250 mm. The settlements after 5 years in the three zones are shown in Figs.11–13, with a summary provided in Table 4.

Consolidation settlement that was within the allowable settlement was recorded in several boreholes: 1) in the backswamp/swamp (Dong Thap province), where settlement was in the range 164–196 mm; and 2) in the sand dune (Tra Vinh province), where settlement was in the range 97–120 mm. These boreholes did not require soil improvement.

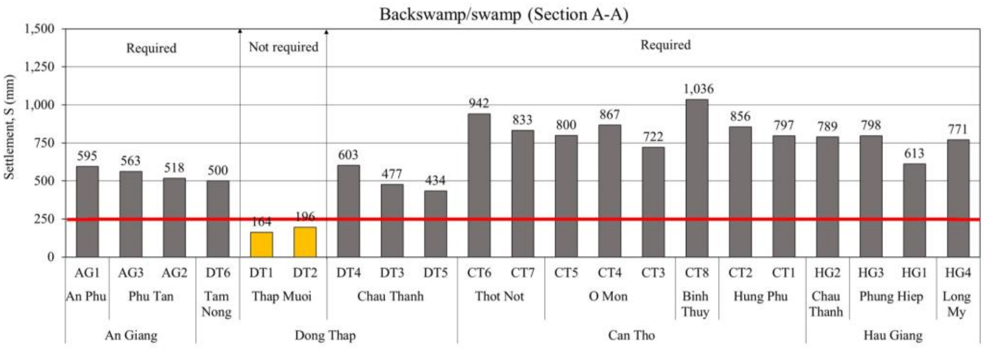



Fig.11 Settlement for 5 years post-construction in backswamp/swamp landform, where red horizontal line indicates maximum acceptable level.

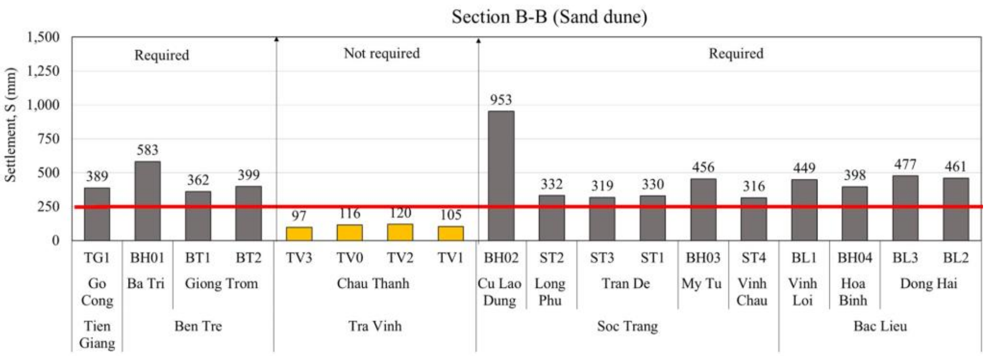



Fig.12 Settlement for 5 years post-construction in sand dune landform, where red horizontal line indicates maximum acceptable level.

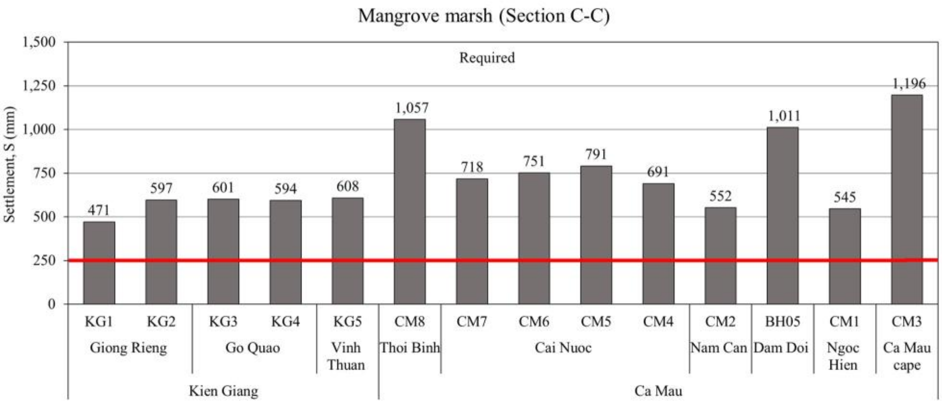



Fig.13 Settlement for 5 years post-construction in mangrove marsh landform, where red horizontal line indicates maximum acceptable level.

Table 4 Summary of 5 years post-construction settlement

| Landform | 5-years post-construction settlement (mm) | | | | | Improvement location (boreholes) | |
|---|---|---|---|---|---|---|---|
| | Ave. U (%) | Min. | Max. | Ave. | Remaining settlement ($\Delta S$) | Required | Not required |
| Backswamp/ swamp | 88 | 164 | 1,036 | 661 | 22–137 | AG1, AG3, AG2, DT6, DT4, DT3, DT5, CT6, CT7, CT5, CT4, CT3, CT8, CT2, CT1, HG2, HG3, HG1, HG4. | DT1, DT2 |
| Sand dune | 90 | 97 | 953 | 370 | 10–96 | TG1, BH01, BT1, BT2, BH02, ST2, ST3, ST1, BH03, ST4, BL1, BH04, BL3, BL2 | TV3, TV0, TV2, TV1 |
| Mangrove marsh | 87 | 471 | 1,196 | 727 | 66–168 | KG1, KG2, KG3, KG4, KG5, CM8, CM7, CM6, CM5, CM4, CM2, BH05, CM1, CM3 | |

*Note: Ave. U (%), Average degree of consolidation, Min., Minimum; Max., Maximum; Ave., Average,* $\Delta S = (1 - U)S_c$

Consolidation settlement exceed the allowable settlement in several landform areas: 1) in the backswamp/swamp, where some boreholes in An Giang, Dong Thap, and Hau Giang Provinces and in Can Tho City experienced settlement in the range 434–1,036 mm; 2) in the sand dune, where settlement was mostly in the range 316–953 mm, as observed in Tien Giang, Ben Tre, Soc Trang, and Bac Lieu Provinces; and 3) in the mangrove marsh, where consolidation settlement was in the range 471–1,196 mm, in the boreholes in Kien Giang and Ca Mau Provinces. Further consideration is needed to address the consolidation settlements that exceed the criteria, particularly in the mangrove marsh landform.

### 8.3 Settlement Improvement Using PVDs

This paper focused on applying PVDs to improve soft ground settlement. This process involves the installation of PVDs to the desired depth, then placing a sand blanket on the exposed ground surface. Subsequently, a road embankment is constructed as a preloading surcharge and the settlement is monitored until the desired settlement level is achieved. As a result, the seepage flow within the ground is primarily from vertical to horizontal. As indicated in Table 2, the horizontal and vertical permeability ratio was 3 ($k_h/k_v = 3$). Consequently, the coefficient consolidation ratio of horizontal to vertical consolidation ($C_h/C_v$) was also 3.

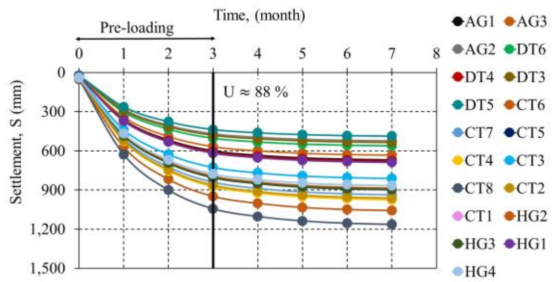



Fig.14 Consolidation using PVDs in backswamp/swamp landform.

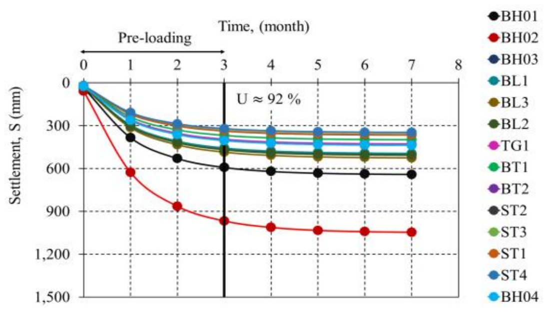



Fig.15 Consolidation using PVDs in sand dune landform.

Table 5 Settlements and remaining settlement after preloading using PVDs periods in each landform.

| Time | Backswamp/swamp | | | Sand dune | | | Mangrove marsh | | |
|---|---|---|---|---|---|---|---|---|---|
| (month) | U (%) | Settlement (mm) | Remaining settlement (mm) | U (%) | Settlement (mm) | Remaining settlement (mm) | U (%) | Settlement (mm) | Remaining settlement (mm) |
| 1 | 54 | 263–628 | 228–545 | 60 | 208–626 | 141–423 | 53 | 283–718 | 254–646 |
| 2 | 77 | 377–900 | 114–273 | 82 | 287–864 | 62–185 | 76 | 408–1,035 | 130–329 |
| **3** | **88** | **437–1,044** | **54–130** | **92** | **321–966** | **27–83** | **87** | **470–1,194** | **67–170** |
| 4 | 94 | 462–1,103 | 30–71 | 96 | 336–1,012 | 12–37 | 94 | 502–1,276 | 35–88 |
| 5 | 97 | 476–1,138 | 15–36 | 98 | 343–1,032 | 6–17 | 97 | 519–1,318 | 18–46 |
| 6 | 98 | 484–1,155 | 8–19 | 99 | 346–1,041 | 3–8 | 98 | 528–1,340 | 9–24 |
| 7 | 99 | 487–1,164 | 4–10 | – | – | 2–5 | 99 | 532–1,351 | 5–13 |

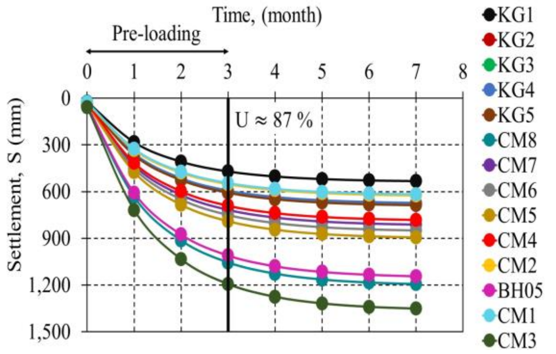



Fig.16 Consolidation using PVDs in mangrove marsh landform.

The results of settlement improvement utilizing PVDs are illustrated in Figs.14–16, and a summary is provided in Table 5. In the backswamp/swamp landform (encompassing An Giang and Hau Giang Provinces, as well as Can Tho City), a consolidation of 88% was achieved within 5 years. However, with the implementation of PVDs, the consolidation time could be substantially reduced to approximately 3 months (Fig.14). Similarly, in the sand dune and mangrove marsh landforms, consolidation percentages of 90% and 87%, respectively, could be attained within 3 months (Figs. 15, 16).

Following 3 months of improvement using PVDs, the remaining settlement amounts in the backswamp/swamp, sand dune, and mangrove marsh landforms were within the acceptable limits. Specifically, the remaining settlements were in the ranges 54–130 mm, 27–83 mm, and 67–170 mm for backswamp/swamp, sand dune, and mangrove marsh, respectively. Notably, these settlement values are well below the allowable threshold of 250 mm, indicating the effectiveness of the PVDs in mitigating settlement issues in these soft ground conditions.

Utilizing PVDs offers an environmentally friendly approach compared to other methods. They facilitate water drainage without any harmful discharge to the local ecosystem, including mangrove trees. However, it is essential to note that the installation process involves pushing a steel mandrel into the clay layer, which can disturb the soil structure and create a 'smear' zone. Careful attention is required during installation to mitigate such potential effects.

## 9. CONCLUSIONS

These findings provide valuable insights for the design and construction of infrastructure projects in the Mekong Delta, emphasizing the effectiveness of PVDs in accelerating consolidation settlement and ensuring the stability of highway embankments. The main conclusions are:

(1) The thickness of soft clay varied across different landforms: backswamp/swamp (8–16.2 m), sand dune (2.5–22 m), and mangrove marsh (6–25 m).

(2) Water content and compression index varied across landforms.

- Sand dunes had a water content range of 36.58–83.96% and a compression index range of 0.12–0.49, lower than other landforms.

- In contrast, mangrove marsh with thick recent clay deposits exhibited higher water content (30.62–105.91%) and compression index (0.17–0.65).

(3) The total primary consolidation settlement for highway embankments in backswamp/swamp, sand dune, and mangrove marsh were in the ranges 186–1,174 mm, 107–1,049 mm, and 537–1,364 mm, respectively. The weathered clay layer contributed around 5–10% of the total settlement, with settlement in the ranges 12–94 mm, 8–99 mm, and 56–123 mm, respectively. The settlement rate in weathered clay would be much faster than in soft clay (typically NC). Engineers should focus on predicting the settlement of the soft clay layer (typically NC), as a major concern in civil engineering.

(4) The consolidation process achieved 88%, 90%, and 87% of the total settlement within 5 years post-construction for the backswamp/swamp, sand dune, and mangrove marsh landforms, respectively. However, these settlement values exceeded the allowable limit for highway standards. Thus, PVD improvement was proposed to accelerate the settlement.

(5) Implementing PVDs would result in settlements of 88%, 92%, and 87% within 3 months for the backswamp/swamp, sand dune, and mangrove marsh landforms, respectively. After 3 months of preloading, the remaining settlement would remain within the allowable limit (less than 250 mm).

(6) Varied landform based PVDs findings offer crucial construction insights. In addition, consider

strength, and permeability factors to ensure embankment stability. These guidelines ensure resilient structures, offering solutions for soft ground challenges in future highway projects.

## 10. ACKNOWLEDGMENTS

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