MINISTRY OF EDUCATION AND TRAINING
HO CHI MINH CITY
UNIVERSITY OF TECHNOLOGY AND EDUCATION

NGUYEN THANH TU

IMPROVEMENT METHODS TO REINFORCE RIVERBED SILTY SOIL USING GEOTEXTILE - CEMENT- SAND CUSHION

MAJOR: CIVIL ENGINEERING - 9580201

SUMMARY OF PH.D THESIS

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This dissertation was completed at the Faculty of Civil Engineering at the **HCM City University of Technology and Education** in Vietnam.

Supervisor 1: Dr. NGUYEN MINH DUC
Supervisor 2: Dr. TRAN VAN TIENG

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LIST OF PUBLICATIONS

The publications related to this dissertation are:

International Journal

1. T. Nguyen Thanh, D. Nguyen Minh, T. Nguyen, and C. Phan Thanh, "Interface Shear Strength Behavior of Cement-Treated Soil under Consolidated Drained Conditions," *Buildings*, vol. 13, no. 7, 2023, doi: https://doi.org/10.3390/buildings13071626.

International Conference

2. T. Nguyen Thanh, D. Nguyen Minh, and T. Le Huu, "The Effects of Soaking Process on the Bearing Capacity of Soft Clay Reinforced by Nonwoven Geotextile," Lecture Notes in Civil Engineering, vol. 62, pp. 669–676, 2020, doi: 10.1007/978-981-15-2184-3_87.
3. T. Nguyen Thanh and D. Nguyen Minh, "Effects of Soaking Process on CBR Behavior of Geotextile Reinforced Clay with Sand Cushion," Proceedings of 2020 5th International Conference on Green Technology and Sustainable Development, GTSD 2020, pp. 162–167, 2020, doi: 10.1109/GTSD50082.2020.9303053

National Journal

4. T. Nguyễn Thanh, Đ. Nguyễn Minh, T. Trần Văn, and B. Lê Phương, "Ứng xử cố kết của đất sét lòng sông khi gia cường đệm cát và vải địa kỹ thuật dưới điều kiện nén 3 trục," Tạp chí Vật liệu và Xây dựng, vol. 4, pp. 90–97, 2021. Available: http://ojs.jomc.vn/index.php/vn/article/view/159
5. T. Nguyễn Thanh, Đ. Nguyễn Minh, N. Mai Trần, T. Trần Văn, and P. Lê, "Ảnh hưởng của bão hoà đến sức kháng cắt không thoát nước của đất bùn sét lòng sông gia cường vải địa kỹ thuật trong điều kiện nén 3 trục," Tạp chí Xây dựng, vol. 5. pp. 68–71, 2022. Available: https://tapchixaydung.vn/anh-huong-cua-bao-hoa-den-suc-khang-cat-khong-thoat-nuoc-cua-dat-bun-set-long-song-gia-cuong-vai-dia-ky-thuat-trong-dieu-kien-nen-3-truc-20201224000011282.html.

CHAPTER 1: INTRODUCTION

1.1. An overview of the research direction:

Nowadays, the demand for building sand in Vietnam is extremely high. Actually, many road construction projects are facing the situation of needing more sand for backfill material. It will be beneficial if riverbed soil is substituted for sand. However, the silty soil from the riverbed has a high void ratio and poor shear strength, creating instability and excess settlement for the works. When using riverbed soil to replace sand as a backfill, reinforced methods should be taken to strengthen the soil's capacity.

1.2. Reinforced methods

There are three noteworthy methods to improve its strength, including geotextile, sand cushion, and cement reinforcement, since they are cheap and popular.

1.2.1. Geotextile reinforcement

Geotextiles can perform a drainage role to maintain and even improve the shear strength of the subsoil, enhancing long-term structural stability. Soil holding capacity and permeability coefficient are two evaluation criteria for the features of geotextiles.

1.2.2. Sand cushion reinforcement:

The sand cushion is a mixture, including sand between two layers of geotextile. The sand cushion, like the geotextile, functions as a drainage border, forcing the pore water pressure to release rapidly.

1.2.3. Cement reinforcement

This technique combines cement and soil in a particular proportion to form a soil-cement mixture with a greater load capacity. The cement and aggregate mixture considerably increase the strength and bearing capability of the clay via the hydration process. This technique is also used to reduce the structure's settlement.

1.3. The urgency of the research

Using riverbed soil instead of sand for backfill material has brought numerous benefits, particularly in the South Vietnam. For example, it helps to solve the problem of lacking sand on many roads. However, riverbed mud exhibits poor characteristics. Reinforcement techniques, including geotextiles, sand cushions, and cement, need to be researched and applied to improve soil capacity.

1.4. Specification of road embankments

1.4.1. Road classification

Rural roads are defined and categorized by TCVN 10380:2014 [6].

1.4.2. Road embankment specifications:

TCVN 4054:2005, TCVN 9436-2012 specify the regulations for the pavement layers.

1.5. Literature review

1.5.1. International research:

a) Using riverbed soil as a backfill material for road construction:

It is common practice to use riverbed soil for road construction and land reclamation [5]. Methods of reinforcement are utilized to strengthen the strength and speed the consolidation of this backfill soil [8, 9].

b) Side friction in one-dimensional consolidation test

The standard of the one-dimensional consolidation test specifies a minimum specimen diameter-to-height ratio, D/H_0, of 2.5 to reduce the effects of side friction. For geotextiles and sand cushions, the samples are usually high. The side friction would significantly reduce the applied consolidation pressure. Thus, it is crucial to evaluate the side friction and the uniform void ratio condition when D/H_0 is greater than 2.5.

c) Geotextile reinforcement method:

Geotextile reinforcement is widely used due to its essential qualities, which include filtration, drainage, separation, and reinforcing of soil layers.

d) Sand cushion reinforcement method:

Numerous studies confirm the drainage function of geotextiles and sand cushions in enhancing the structure's load capacity and stability.

e) Soil-cement mixture

Cement is commonly used to increase soft soils' strength, stiffness, and stability. The shear strength of the soil-steel interface was evaluated utilizing the modified direct shear test apparatus, in which the lower portions of the conventional direct shear box were replaced with a steel plate. However, prior research rarely assessed the shear strength of the cement-treated soil-steel interface.

1.5.2. National research:

Geotextiles, sand cushions, and cement have been widely researched for basement applications, for example, Vinh [85], Nguyen Minh Duc et al. [89], Nguyen et al. [93]…

1.5.3. Comments:

Although there were some studies about the soil reinforced by geotextile, sand cushion, and cement, these methods were not entirely investigated.

1.6. Research objectives

1.6.1. Goals of the dissertation

The research objectives are:

- Consolidation behavior of clay under the effects of side friction: analysis of friction pressure and non-uniform void ratio.
- Effect of geotextile reinforcement on swelling, *CBR* value, *UU* shear strength in saturated and unsaturated conditions, and saturated soil consolidation.
- Effect of sand cushion reinforcement on swelling, *CBR* value, *UU* shear strength in saturated and unsaturated conditions, and saturated soil consolidation.
- Effect of cement reinforcement on swelling, *CBR* value, *UU* shear strength in saturated and unsaturated conditions, and saturated soil consolidation. Additionally, direct shear tests were performed to investigate the behavior of the shear strength of soil cement and the interface shear strength between soil cement and steel under consolidated, drained conditions.

1.6.2. Research scope

This research investigated the soil from the Cai Lon River in Kien Giang Province by using remolded samples. The outcome of the research would be the basic theory to enhance the soft soil from riverbeds for the backfill. In this research, the consolidation settlement under permanent loads will be investigated.

CHAPTER 2: MATERIALS – THEORIES- MODIFIED DEVICES

2.1. Material

2.1.1. Riverbed soil

a) Soil properties: Soil was collected from the CaiLon River in southern Vietnam.

b) Process of remolding silty soil.

2.1.2. Geotextile

A nonwoven, needle-punched Polyethylene terephthalate geotextile was utilized.

2.1.3. Uniform quart sand

Sand is classified as SP type according to the Unified Soil Classification System.

2.1.4. Ordinary Portland cement

Normal Portland cement PC40 was used in this study (ASTM C188 [100]).

2.2. Experimental theories

2.2.1. California Bearing Ratio test:

2.2.2. One-dimensional consolidation theory

a) Consolidation process: the process of reducing the volume of saturated soil due to water flowing out of the soil without the rearrangement of soil particles.

b) One-dimensional consolidation test

The minimum diameter-to-height ratio shall be 2.5 to reduce the impact of friction between the specimen's periphery and the inside of the ring.

c) Determine the coefficient of consolidation C_v

2.2.3. Triaxial compression test – Modified triaxial apparatus:

a) Triaxial compression test:

A triaxial compression test is used to determine the shear strength parameters.

b) Modified triaxial apparatus:

A modified triaxial schematic is introduced, in which there is a small pipe from the middle of the sample to the device to measure the pore water pressure.

c) Unconsolidated-Undrained test (UU) for unsaturated samples

The strain rate in UU tests is typically 1% per minute.

d) Unconsolidated- Undrained test (UU) for saturated samples

2.2.4. Direct shear test

2.3. Modified shear box for friction between the soil and steel

A modified shear box was developed to evaluate the shear strength of the interface between untreated or cement-treated soil and stainless steel. The original lower shear box has been replaced with a stainless steel plate.

2.4. Modified oedometer apparatus for side friction pressure measurement

A modified oedometer apparatus was developed to measure the side friction between the soil and the consolidation ring, as shown in Figure 2.13:

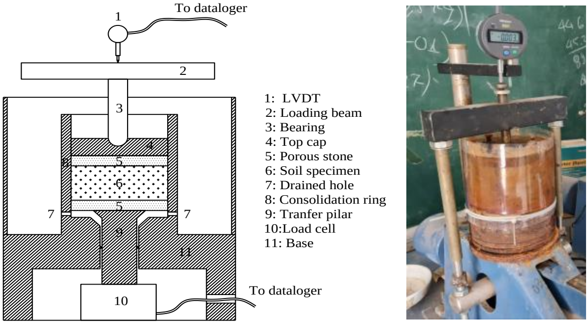

Figure 2.13: Modified oedometer apparatus for side friction pressure measurement

CHAPTER 3: BEHAVIOR OF SILTY SOIL WITH AND WITHOUT GEOTEXTILE UNDER CBR, UU, AND CONSOLIDATION TESTS

3.1. Introduction

The research objectives of this chapter are:

- Effect of nonwoven geotextile on soil's swelling and *CBR* value in unsaturated and saturated conditions by the *CBR* test.
- Effect of nonwoven geotextile on the *UU* shear strength in unsaturated and saturated conditions by triaxial test to evaluate the soil capacity.
- Effect of side friction on the consolidation behavior of clay. A modified Taylor's method is presented to predict the friction pressure and determine the void ratio distribution without requiring the specimen height at the end of the tests. Furthermore, the study proposed an analytical equation to evaluate the *COV* values to quantify the degrees of uniformity of the void ratio along the depth of the specimens in the one-dimensional consolidation experiments.
- Effect of geotextile under the one-dimensional consolidation test.

3.2. Experimental program

3.2.1. *CBR* specimens

There were a total of 10 specimens for soaked and unsoaked conditions, including soil samples and geotextile-soil samples. In every group, there were unreinforced samples and geotextile-reinforced samples with 1, 2, 3, and 5 layers.

3.2.2. Unconsolidated-Undrained shear strength samples in triaxial test

There were 20 samples, including unreinforced samples, 1-layer, 2-layer, and 3-layer reinforced samples, with two initial conditions and compression pressure:

- *Unsaturated samples*: samples will be tested at lateral pressure of 50 kPa, 100 kPa, 150 kPa, and 200 kPa, respectively.
- *Saturated samples*: samples will be tested at 300 kPa of lateral pressure.

3.2.3. Consolidation samples

a) Samples to investigate the soil consolidation behavior under the effects of side friction:

The height of the soil was 10, 20, 30, 40, and 50 mm. The diameters of the samples were 50 and 75 mm.

b) Samples to investigate the effect of nonwoven geotextile on the soil consolidation process.

There were 3 samples, including unreinforced soil and soil reinforced by 1, and 3 geotextile layers.

3.3. Behavior of silty soil with and without geotextile under the swelling and *CBR* test

3.3.1. Influence of the geotextile on the behavior of the soil swell

At the initial time, the percent swell of unreinforced specimens was smaller than that of reinforced specimens. After 96 hours, the final swell of reinforced specimens was observed to be reduced with the number of reinforcement layers.

3.3.2. CBR behavior of unreinforced and reinforced silty soil by geotextile in un-soaked and soaked condition:

The higher the number of reinforcements, the higher the bearing capacity of reinforced specimens. The nonwoven geotextile improved the bearing capacity of soaked clay more effectively than that of unsoaked clay specimens.

The optimum ratio between reinforcement spacing and the diameter of the load piston for the highest strength ratio was about 0.8 (equivalent to the specimen reinforced by 2 geotextile layers) due to confinement and the membrane effect.

3.3.3. The effect of soaking on CBR behavior:

After soaking, the *CBR* value dramatically plunged and geotextiles improved the *CBR* value.

3.4. Behavior of silty soil with and without geotextile on UU shear strength under triaxial test

3.4.1. The shear strength behavior of silty soil unreinforced and reinforced by geotextiles in the unsaturated condition:

a) Shear strength behavior of silty soil unreinforced and reinforced by geotextile in the unsaturated condition:

The deviation stress increased as the lateral pressure σ_3 and the number of geotextile layers increased.

b) The shear strength increasement R_{uf} in the unsaturated condition:

Results indicated that R_{uf} was greater than 1, showing that the reinforcement layers can increase the soil's strength. The R_{uf} value decreased as lateral pressure increased. The R_{uf} value increased as the number of fabric layers increased.

3.4.2. The shear strength behavior of silty soil unreinforced and reinforced by geotextile in the saturated condition.

a) Shear strength behavior of silty soil unreinforced and reinforced by geotextile in the saturated condition.

As the number of geotextile layers increased, the UU shear strength and the excess pore water pressure increased. In the strain range of 1% to 3%, the reinforced sample generated a higher water pressure than the unreinforced sample, as the geotextile prevented lateral expansion of the sample. As the strain increased, the soil sample developed lateral strain (sliding between the soil and geotextile), which decreased the water pressure.

b) The shear strength increasement R_f in the saturated condition:

The R_f index increased as the number of layers surged.

3.4.3. Shear strength reduction of silty soil and geotextile soil due to saturation

The results showed that the shear strengths of saturated samples were much lower than those of unsaturated ones, about 57 % - 83%.

3.5. Consolidation behavior of silty soil under effects of side friction

3.5.1. The one-dimensional consolidation behavior under the effects of side friction pressure

a) The strain of specimens: The smaller axial strain was observed in the soil with the higher initial height and the smaller diameter due to side friction.

b) The coefficient of consolidation: the higher the average consolidation pressure, the lower the coefficient of consolidation.

c) The void ratio at the end of the primary consolidation (EOP):

The void ratio at EOP of the specimens with the initial height, $H_0 \geq 30$mm, was significantly higher than those with a lower H_0. It illustrates that for the cases of $H_0 \geq 30$mm, the friction was high enough to cause a significant reduction in the actual consolidation pressure.

d) Coefficient index:

The compression curves of all the soil specimens converged into a unique curve when using the average consolidation pressure to correct the compression curves.

3.5.2. The total friction pressure and the friction pressure loss ratio

The value of T slightly increased with consolidation time due to the increment in the effective stress caused by water pressure dissipation. The higher friction pressure was obtained for specimens with higher thicknesses and smaller diameters.

3.5.3. Friction between the soil and steel, measured by modified shear device:

The effective friction angle of the clay and the interface friction angle between the clay and the stainless steel, ϕ'_{int}, were 27.6^0 and 16.5^0, respectively.

3.5.4. Modified Taylor's method to evaluate friction pressure loss ratio:

The height of soil specimens at the end of primary consolidation (EOP), *H*, can be estimated by:

$$H = \alpha\left(1 - \frac{C_c}{1+e_0} log \frac{P}{P_0}\right) H_o \tag{3.16}$$

In which $\alpha = \frac{1}{1 - \frac{C_c}{1+e_0}\frac{2H_0}{D \ln 10} K_0 \tan \varphi'_{int}}$ (3.15)

The friction pressure loss ratio, *r*, would be modified:

$$r_{EOP} = 1 - e^{\frac{-4H_0}{D}\alpha\left(1 - \frac{C_c}{1+e_0} log \frac{P}{P_0}\right) K_0 \tan \varphi'_{int}} \tag{3.18}$$

3.5.5. The non-uniform density in the specimens caused by side friction:

The void ratio of soil at depth *z* could be determined:

$$e_z = e_P + \frac{4z}{D \ln 10} K_0 \tan \phi'_{int} C_c \tag{3.19}$$

The average value of the void ratio:

$$e_{EOP\_predicted} = e_P + C_c \frac{2H_0}{D \ln 10} \alpha K_0 \tan \phi'_{int} \quad (3.20)$$

The void ratio would increase proportionally with the depth. (self-weight ≅0)

3.5.6. The coefficient of variation, *COV*:

The coefficient of variation, *COV*, could be evaluated:

$$COV = \frac{2H}{\sqrt{3} \ln 10 D e_{EOP}} K_0 \tan \varphi'_{int} C_c \quad (3.23)$$

The specimens subjected to a higher compression pressure, *P*, would exhibit a greater coefficient of variation. The requirement of $D/H_0 \geq 2.5$ not only ensures the homogeneity void ratio in the specimens (i.e., *COV*<1.2%), but it also limits the loss of consolidation pressure at EOP due to side friction to less than 21%.

3.6. Behavior of silty soil with and without geotextile under one dimensional consolidation test

3.6.1. Primary consolidation

Consolidation time was reduced by approximately 1.5 to 2 times when adding a layer of geotextile.

3.6.2. Consolidation coefficient C_v:

The consolidation coefficient C_v increased due to its enhanced permeability. As the load increased, the C_v reduced.

3.7. Conclusion

A series of tests, including *CBR*, UU triaxial, and consolidation tests, were performed to confirm that geotextile can improve the soft soil’s capacity and consolidation. Additionally, the side friction was significantly higher for soil with *D/H* < 2.5 in the one-dimensional consolidation test.

CHAPTER 4: BEHAVIOR OF SILTY SOIL WITH AND WITHOUT SAND CUSHION UNDER CBR, UU, AND CONSOLIDATION TEST

4.1. Introduction

The research objectives of this chapter are:

- Effect of sand cushion on soil's swelling and *CBR* value in unsaturated and saturated conditions by the *CBR* test.
- Effect of sand cushion on the UU shear strength in unsaturated and saturated conditions by triaxial test to evaluate the soil capacity when constructed fast.
- Effect of sand cushion under the one-dimensional consolidation test.

4.2. Experimental program

4.2.1. *CBR* specimens

8 specimens were reinforced with cushion sand for soaked and unsoaked conditions. The thickness of the sand cushion varied, including 10mm, 15mm, 20mm, and 40 mm.

4.2.2. Unconsolidated-Undrained shear strength samples in triaxial test

There were 15 sand cushion samples, with sand thicknesses ranging from 5mm to 10 mm and 20 mm. There were 2 types of tests, as follows:

- *Unsaturated samples*: samples will be tested at lateral pressures of 50 kPa, 100 kPa, 150 kPa, and 200 kPa.
- *Saturated samples*: samples will be tested at 300 kPa lateral pressure.

4.2.3. Consolidation samples

A layer of 10mm and 20mm sand was placed between geotextiles in the middle of the soil. The total height of the specimens was 40mm.

4.3. Behavior of silty soil with and without sand cushion under the swelling and CBR test

4.3.1. Influence of the sand cushion on the swell behavior

The swells of the reinforced specimens were slightly smaller than those of the soil due to the local lateral confinement from soil-reinforcement interaction.

4.3.2. The CBR behavior of unreinforced and reinforced specimens

Due to the reinforcement, the *CBR* value of reinforced specimens was higher than that of unreinforced specimens. Interestingly, the bearing capacity of the specimens was the highest for the specimens reinforced by a 1.5 cm thickness of the sand cushion, of which the ratio of the height of the topsoil layer and the diameter of the penetrated piston was equal to 1.

4.3.3. Influences of soaking on the CBR behavior of unreinforced and reinforced specimens

Compared to the unsoaked specimens, the CBR value of the soaked specimens was much smaller, demonstrating the extreme reduction of strength when saturated. The sand cushion not only enhanced the bearing capacity under both conditions but also minimized the strength reduction of the soil after soaking.

4.4. Behavior of silty soil with and without sand cushion on UU shear strength under the triaxial test

4.4.1. The shear strength behavior of silty soil reinforced with a sand cushion in the unsaturated condition.

a) Shear strength behavior of unsaturated soil reinforced by a sand cushion:

The deviation stress increased as the lateral pressure σ_3 and the thickness of the sand cushion increased.

b) The shear strength increasement R_{uf} in the unsaturated condition.

R_{uf} was greater than 1 at all lateral pressures, showing that the reinforcement can increase the soil's strength. The R_{uf} value decreased as the lateral pressure increased. The R_{uf} value increased as the thickness of the sand increased.

4.4.2. The shear strength behavior of silty soil reinforced by a sand cushion in the saturated condition.

a) Shear strength behavior of the saturated soil reinforced by the sand cushion.

Deviation stress increased when the axial strain and the thickness of the sand cushion increased. As the thickness of the sand cushion increased, the UU shear strength and the excess pore water pressure increased. The sand cushion prevented lateral expansion of the samples.

b) The shear strength increasement R_f in the saturated condition.

The strength increase index R_f increased as the thickness of the sand increased when comparing the strength of unreinforced soil.

4.4.3. Shear strength reduction of soil and sand cushion soil due to saturation:

After soaking, the shear strength decreased. The larger the lateral stress and the smaller the sand thickness were, the higher the strength reduction T_{shear} was.

4.5. Behavior of silty soil with and without sand cushion under one – dimensional consolidation test

4.5.1. Estimate the height and bottom pressure of the sand cushion under load:

The height (h_{sand}) and the bottom pressure (P_{b_sand}) of the sand cushion under compression load P_{t_sand} can be predicted, with an error of under 7%.

4.5.2. The average pressure in soil and sand cushion

Due to the side friction between the soil, specifically sand, and the ring, the lost compression pressure must be considered.

The friction pressure in the sand cushion layer was much higher than that of the upper and lower soil, up to 1.9 times, leading to a high loss pressure in the average compression pressure, about 20%.

4.5.3. The effect of the sand cushion on the silty soil consolidation process

a) Primary consolidation: The results indicated that consolidation was accelerated in the reinforced samples.

b) Consolidation coefficient C_v: The consolidation coefficient C_v rose due to its increased permeability. As the load increased, the C_v decreased.

4.6. Conclusion:

A series of tests, including *CBR*, UU triaxial, and consolidation tests, were performed to confirm that the sand cushion can improve the soft soil's capacity in both soaked and unsoaked conditions and the consolidation process.

CHAPTER 5: BEHAVIOR OF SILTY SOIL REINFORCED BY CEMENT UNDER CBR, UU, CONSOLIDATION, AND SHEAR TEST

5.1. Introduction

The research objectives of this chapter are:

- Effect of cement ratio on soil's swelling and *CBR* value in unsaturated and saturated conditions by the *CBR* test.
- Effect of cement ratio on the *UU* shear strength in unsaturated and saturated conditions by triaxial test to evaluate the soil capacity.
- The behavior of soil cement on the one-dimensional consolidation test.
- The effects of cement content and curing time on the shear strength behavior of the cement-treated clay and steel interface. In addition, grain size analysis was conducted on the treated soil samples to reveal the effects of cement treatment on improving their structure, which led to an increase in shear strength. Using the peak and residual strength values, the brittleness of the treated soil was also evaluated. In addition, a correlation equation would be proposed to quantify the rate of shear strength and interface shear strength development in cement-treated soil specimens with curing time.

5.2. Experimental program

5.2.1. CBR specimens:

Three specimens were reinforced with cement under wet conditions. The dried weight ratio of soil to cement was 3%, 5%, and 10%.

5.2.2. Unconsolidated-Undrained shear strength samples in triaxial test

The dried weight ratio of cement to soil was 3%, 5%, and 10%. After 28 days, the samples were tested. There were two types of tests, as follows:

- *Unsaturated samples*: samples will be tested at lateral pressures of 50 kPa, 100 kPa, 150 kPa, and 200 kPa, respectively.
- *Saturated samples*: samples will be tested at 300 kPa lateral pressure.

5.2.3. Consolidation samples

There were 4 specimens with dry cement at 3%, 5%, 7%, and 10%. The sample dimensions were 50mm in diameter and 20mm in height.

5.2.4. Direct shear and interface shear samples

The number of samples was displayed as in Table 5.1:

Table 5.1: Testing program

Material	Cement content, c_m (%)	Effective normal stress (kPa)	Curing period (days)
Type of test: Direct shear test under consolidated drained condition			
Untreated soil	0%	50, 100, 150, and 200	0
Cement-treated soil	10%	200	3, 7, 14, 28, and 56
Cement-treated soil	3%, 5%, 7%, and 10%	50, 100, 150, and 200	28
Type of test: Interface shear test under consolidated drained condition			
Untreated soil vs. stainless steel	0%	50, 100, 150, and 200	0
Cement-treated soil vs. stainless steel	10%	200	3, 7, 14, 28, and 56
Cement-treated soil vs. stainless steel	3%, 5%, 7%, and 10%	50, 100, 150, and 200	28

5.3. Behavior of silty soil with cement under the swelling and CBR test

5.3.1. Influence of cement on the soil's swell behavior

At the initial time, the percent swell of unreinforced specimens was smaller than that of reinforced specimens. However, after about 20 hours, more swell was found in the unreinforced specimens. After 96 hours, the final swell of reinforced specimens was observed to be reduced with the higher ratio of cement.

5.3.2. The CBR behavior of unreinforced and reinforced specimens

For soaked specimens, at 28 days of curing time, the bearing capacity of the soil was significantly improved when reinforced by cement. The higher the cement content was, the higher the bearing capacity of reinforced specimens would be. When the cement ratio increased to 3%, 5%, and 10%, the CBR values went up 1.7, 3.4, and 3.8 times.

5.4. Behavior of silty soil with cement on UU shear strength under the triaxial test

5.4.1. The shear strength behavior of unsaturated soil reinforced by cement:

a) Shear strength behavior of unsaturated soil reinforced by cement:

When the cement content increased, the sample exhibited brittle failure with minimal deformation at a horizontal pressure of 50 kPa. As lateral pressure rose, the strain at failure increased. When the cement content increased, its strength increased dramatically.

When cement was presented, the cohesive force increased rapidly. However, the angle of internal friction was stable, about 24^0 with 3% and 5% cement, before increasing slightly to 26.4^o at 10% cement.

b) The shear strength increasement R_{uf} in the unsaturated condition.

Results indicated that R_{uf} was greater than 1 at all lateral pressures, showing that the soil's strength was improved. The R_{uf} value decreased as the lateral pressure increased. The R_{uf} value increased as the cement content increased.

5.4.2. The shear strength behavior of silty soil reinforced by cement in the saturated condition.

a) Shear strength behavior of saturated soil reinforced by cement.

Deviation stress increased when the axial strain and the cement content increased. The larger the strain and the cement content were, the higher the deviation was.

b) The shear strength increasement R_f in the saturated condition.

The strength increment index R_f was the ratio between deviations of soil cement and soil at failure. The R_f index increased with the cement ratio increment.

5.4.3. Shear strength reduction of silty soil and cemented soil due to saturation:

Shear strength reduction T_{shear} was smaller than 1. It indicated that, after soaking, the shear strength decreased, and the cement improved the shear strength of the mixture. The larger the lateral stress, the higher the strength reduction was.

5.5. Behavior of soil cement under consolidation test

The soil-cement settles quickly and stabilizes after approximately 30 minutes. It is not possible to determine the consolidation time and consolidation coefficient C_v according to Taylor and Cassagrade's methods due to the limitations of these methods. Instead, secant modulus was characteristic of soil cement. It showed that the modulus of soil cement increased about 2 times, when the cement ratio increased from 3% to 7%, but the modulus in the case of 10% cement was 6 times higher than that of 3% cement at 23.74 kPa.

5.6. Grain size distribution of soil cement mixture

The particle size of the treated soil was larger than that of the untreated soil. It revealed a transition from predominantly clay-sized particles to silt-sized particles due to hydration and pozzolanic processes.

5.7. Interface shear strength behavior of cement-treated soil under consolidated drained conditions

5.7.1. Shear stress-strain behavior of cement stabilized soil under consolidated-drained conditions

After 28 days of curing under various effective normal stresses, at the effective normal stress range of 50-200kPa, the peak shear strength of cement-treated soil specimens was substantially higher than that of untreated soil. More cement content increases the shear strength of treated soil sample. In addition, cement-treatment shifted the stress-strain behavior of the untreated and treated soil specimens from ductile to brittle failure, respectively.

5.7.2. Behavior of interface shear strength between cement-treated silty soil and steel under consolidated-drained conditions.

After 28 days of curing, the interface shear strength of cement-treated soil with steel was greater but reached its maximum value at a smaller shear displacement than that of untreated soil and steel. Moreover, the increase in cement content led to an increase in peak interface shear strength and a reduction in peak shear displacement.

5.7.3. Result of the effect of cement content on the shear strength and interface shear strength of cement-treated soil.

The small effective cohesion of the untreated soil illustrated that the soil was under normal consolidated conditions. For the shear strength of the cement-treated soil, it was manifested by relatively small increases in effective cohesions and significant increases in effective friction angle. Similarly, both the peak and residual effective interface friction angles, ϕ'_{int_max} and ϕ'_{int_res}, were higher when increasing the C_m value. In contrast, the slight increase in effective cohesion under consolidated drained shearing may expose weak particle bonding.

In addition, there was a significant difference between the peak and residual shear strength of the cement-treated soil sample. However, there was a little difference (about 2kPa) between the peak and residual effective cohesiveness of the cement-treated soil, c'_{max} and c'_{res}, a significant difference between the peak and residual effective residual friction angles, ϕ'_{max} and ϕ'_{res}. The difference would be greater as the cement content increased.

The strength ratio of cement-treated soil could also be evaluated using w/C_m:

$$R_s = \frac{15.191}{(w/C_m)^{1.019}} \quad (5.8)$$

5.7.4. Effect curing period on the shear strength and the interface shear strength of cement-treated soil.

The lengthening of the curing period caused the shear and interface shear behavior of the treated soil to become more brittle.

A strong correlation ($R^2 = 0.981$) was found between the curing period and the strength development ratio of peak and residual strength derived from shear strength and interface shear strength of the treated soil samples:

$$R_{SD} = \frac{\tau_D^{max}}{\tau_{28}^{max}} = \frac{\tau_D^{res}}{\tau_{28}^{res}} = \frac{\tau_D^{int\_max}}{\tau_{28}^{int\_max}} = \frac{\tau_D^{res\_int}}{\tau_{28}^{res\_int}} = 0.2108\, ln(D) + 0.2833 \quad (5.9)$$

in which

$\tau^{max}{}_D$, $\tau^{res}{}_D$, $\tau^{int\_max}{}_D$, and $\tau^{int\_res}{}_D$ are the peak shear stress, residual shear stress, peak interface shear stress, and residual interface shear stress after D days of the curing period, respectively,

$\tau^{max}{}_{28}$, $\tau^{res}{}_{28}$, $\tau^{int\_max}{}_{28}$, $\tau^{int\_res}{}_{28}$ are the peak shear stress, residual shear stress, peak interface shear stress, and residual interface shear stress after 28 days of the curing period, respectively.

5.8. Conclusion

A series of laboratory tests were conducted to examine the characteristics of cement-treated silty soil. Due to cement's hydration and pozzolanic reaction, the swelling, CBR value, UU shear strength, settlement and shear strength of the treated soil improved significantly.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Comparison:

After being saturated, silty soil swells and loses its strength, which is unsatisfactory for backfill material. Thus, the primary goal of this research was to evaluate the capacity of reinforcements, including geotextile, sand cushion, and cement, to improve the soil's properties. The laboratory tests, including the *CBR* test, the *UU* triaxial shear strength test, a one-dimensional consolidation test with a modified oedometer apparatus, and the modified direct shear test, were carried out to investigate the reinforcement capacity. The factors for a material backfill are swelling, strength, and the consolidation process, which are discussed as follows:

a) Percentage of swelling

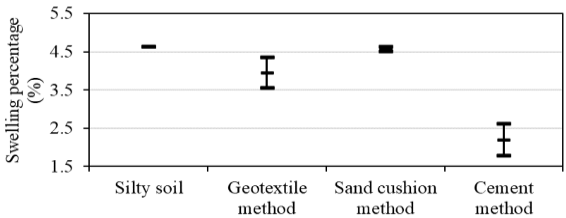

Figure 6.1: The swelling range of reinforcement methods in this study.

These methods reduced the swelling of the soil, reducing density loss after soaking. For the soil reinforced by geotextiles and sand cushions, the permeable reinforcement accelerates swelling by increasing the drainage path within the reinforced specimens. In the soil cement samples, the hydration process occurred and bound the soil grains together, leading to a decrease in the swell. A lower percent expansion was observed as the number of geotextile layers, the sand cushion thickness, and the cement ratio increased. Figure 6.1 shows the highest, average, and lowest swelling of each reinforcement method in this study. The results illustrated that the swellings in the cement method got the lowest values, whereas the sand cushion got the highest numbers.

b) CBR behavior

After soaking, the *CBR* values of the soil decreased dramatically. By using geotextile, sand cushion, and cement, the *CBR* value was significantly improved. Interestingly, for the geotextile-soil mixture, the highest *CBR* value was obtained when the ratio between reinforcement spacing and the diameter of the load piston, achieved the optimum value of about 0.8 (2 geotextile layer samples). The observation can be explained by the mechanisms of reinforced soil under the load of a piston, including the confinement effect and the membrane effect. Under sand cushion reinforcement, again, the maximum improvement happened at the soil with 15 mm of sand cushion, of which the ratio of the height of the topsoil layer and the diameter of the penetrated piston got an optimum value equal to 1. The *CBR* increase in soil reinforced by geotextile and sand cushion in the case of soaking is greater than in the case of unsoaking. For the soil cement, after 28 days of soaking, the *CBR* value increased as the cement ratio increased due to the hydration process.

Comparing these methods, Figure 6.2 showed that the strength of silty soil was improved significantly. The cement method got the highest score. However, the value range of this method was larger than others. The geotextile *CBR* value was the smallest, indicating that increasing the number of geotextile layers did not significantly affect it.

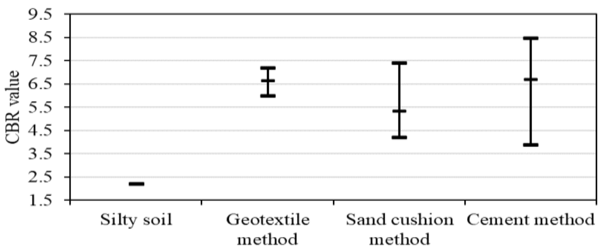

Figure 6.2: The *CBR* range of reinforcement methods for saturated samples

c) UU shear strength

After soaking, the shear strength of the soil decreased dramatically. Geotextile, sand cushion, and cement improved UU shear strength, especially in the case of saturated samples. The shear strength reduction decreased when the lateral pressure decreased, and the number of geotextile layers and sand cushion thickness increased.

For saturated samples, as the number of geotextile layers and the sand thickness increased, the UU shear strength and the excess pore water pressure increased with the small strain, as reinforcements can restrain the lateral deformation or the potential tensile strain of the soil. After that, the pore water pressure decreased. The soil-cement showed a brittle failure with minimal deformation. As the concentration of cement increased, its strength significantly increased. With the saturated samples, the results indicated that deviation stress increased when the axial strain and the cement content increased.

Figure 6.3 shows the UU shear strength S_u in the saturated condition for three methods. It revealed that the cement method gave the best reinforcement effect, whereas the geotextile and sand cushion methods had a lower reinforcement efficiency.

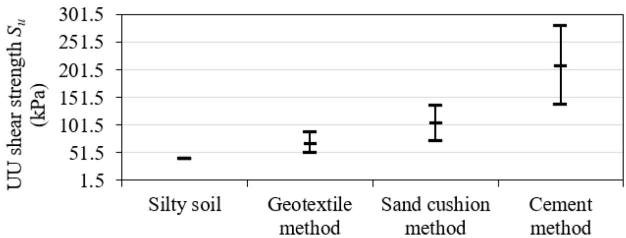

Figure 6.3: The UU shear strength S_u range of reinforcement methods for saturated samples.

d) Consolidation

When estimating the consolidation behavior of silty soils with a D/H_0 greater than 2.5, evaluating the side friction is essential.

In this study, a modified oedometer apparatus was created to determine the side friction between the soil and the consolidation ring. The total side friction pressure grew marginally as consolidation time rose, causing an important reduction in the average consolidation pressure at the end of primary consolidation (*EOP*). As D/H_0 increases, the friction pressure loss ratio at *EOP* decreases. Furthermore, it declined as the compression pressure was raised. Besides, the proposed analytical method can accurately predict the values of r_{EOP} and e_{EOP} for clay within the normal consolidation pressure range without requiring the height of test specimens. Furthermore, the void ratio at the conclusion of primary consolidation increases proportionally with depth due to side friction. Using *COV* values of the void ratio, the degree of soil sample uniformity at the *EOP* was determined. The *COV* values increase as the friction pressure loss ratio increases.

Regarding the effect of geotextile and sand cushion, the consolidation time significantly declined compared to that of soil, by 1-2 times for geotextile samples and 3.5- 5 times for sand cushion samples. Thus, the geotextile and sand cushion, as a drainage path, can improve the soil's capacity and the consolidation process.

In the soil-cement mixture, after roughly 30 minutes, the samples settled rapidly and stabilized. The secant modulus was displayed as one of the characteristics of a soil-cement mixture. When the cement ratio increased, the modulus of soil cement increased. Furthermore, the settlement of the mixture decreased significantly, leading to an increase in the void ratio.

Thus, when comparing the three methods, the cement method had the shortest time to reach consolidation and the smallest settlement.

e) The effects of cement content and curing time on the shear strength behavior of the cement-treated clay and steel interface

Due to the cement's hydration and pozzolanic reaction, the shear strength and interface shear strength of the treated soil specimens improved significantly. The remaining findings were as follows:

- The cement caused the treated soil's particle size to increase. Particularly, after 28 days of curing, the percentage of sand in soil treated with 10% cement decreased twofold. That increment was due to the integration of fines into sand-size particles, which was a result of cement treatment.

- The treated soil's shear strength and interface shear strength exhibited the brittle shear-strain and stick-slip phenomena, respectively. The increase in effective friction angle mostly contributed to the improvement in the shear strength of the soil cement. In contrast, the treated soil exhibited an insignificant increase in effective cohesion.
- The higher the cement content, the greater the shear strength ratio of the soil treated with cement. For specimens containing 3-10% cement, the peak and residual average shear strength ratios ranged from 1.28 to 2.40 and 1.16 to 1.80, respectively. The cement also enhanced the soil-steel interface's strength parameters. At its peak, the average interface efficiency factor was approximately 1.55 when 10% cement content was added.
- The correlation calculation was proposed to estimate the increase in shear strengths based on the ratio of water content to cement weight. Additionally, another proposed equation may be used to predict the rate of shear strength and interface shear strength development in cement-treated silty soil with a curing period.

6.2. Conclusion

Based on the above comparison, in this research, the cement mixing method was the best method to improve the silty riverbed soil. Geotextile and sand cushions could enhance the physical and mechanical behaviors of soil, including swelling, strength, and consolidation.

According to the strength regulations of the pavement layer, the minimum *CBR* load capacity for rural roads with car-free traffic is 6 for the top 30 cm and 4 for the following 50 cm, based on TCVN 4054:2005 [3]. Thus, all the presented methods were applicable to improving the riverbed soil and applied to the foundation for rural roads in the Mekong Delta. Regarding rural roads with car traffic, TCVN 9436-2012 [4] requires the swelling of the backfill material to be lower than 3%. In this case, together with the strength requirement, the cement method with 5% and above could be used as the backfill material.

6.3. Limitations and recommendations:

The results would illustrate the improvement of the soil. Because the water content increases, the silty soil loses its strength. Particularly, the case where the soil was saturated was considered the weakest and most dangerous. Thus, this study just demonstrates the effect of saturation on the strength behavior of reinforced soil. Therefore, this study did not focus on the mechanical behavior of the unsaturated samples when the strength changed. The mechanical behavior of unsaturated samples can be further researched.

Additionally, the outcome of this study would be a fundamental theory to enhance rural road design by using reinforced clay as backfill instead of costly sandy soil for rural road foundations. In the laboratory, the results showed that these methods satisfied the Vietnamese standard. The findings proved that these methods are efficient, quick, and cost-effective. However, the findings cannot be directly used in the design of the road's embankment. To apply these methods in reality, field conditions, construction methods, and field experiments need to be considered. The results of field experiments would be the most accurate basis for applying the methods widely. Thus, there needs to be more applied research about techniques, machines, materials, and field experiments. The result of field experiments would be that the methods could be widely used.