Experimental Investigation of Sand Seam Effects on Consolidation Behavior of Vertical Drain-Installed Soft Soils

Chau Phuong Ngo, Kien-Tai Do, Daeho Yun, Yun-Tae Kim, and Ba-Phu Nguyen

Abstract Thin-layered sand seam in soft deposits can be formed artificially or naturally. It affects significantly the consolidation behavior of subsoil. To investigate the consolidation settlement of soft deposits with thin-layered sand seam, a series of consolidation tests of the layered soft soil-sand systems improved by prefabricated vertical drain (PVDs) is performed. To estimate the effects of thin sand layers, three cases of consolidation tests are carried out as follows: in Case 1, the PVD-soil column is tested without thin sand layer; one and two thin sand layers were placed between the soft soil layers in Case 2 and Case 3, respectively. The experimental results indicate that the rate of consolidation settlement of PVD-installed soft deposit with the thin sand layers is faster than that of the case without sand seam, because the thin sand layers can provide a shorter drainage path for consolidation of the soft soil. As expected, this result is obviously appeared in Case 3. However, the final settlement of PVD-installed soft soil with thin sand layers is smaller than that of the case without sand seam. It can be seen that the existence of thin sand layers interbedded with soft soil layer can improve the strength of soft soil.

Keywords Geosynthetics · Soft soil · Sand seam · Consolidation · Settlement · Vertical drain

C. P. Ngo
Campus in Ho Chi Minh City, University of Transport and Communications, No. 450−451 Le Van Viet Street, Tang Nhon Phu A Ward, Thu Duc City, Ho Chi Minh City 700000, Vietnam

K.-T. Do · B.-P. Nguyen (✉)
Department of Civil Engineering, Industrial University of Ho Chi Minh City, Ho Chi Minh City 700000, Vietnam
e-mail: nguyenbaphu@iuh.edu.vn

D. Yun · Y.-T. Kim
Department of Ocean Engineering, Pukyong National University, Busan 608−737, Korea

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1 Introduction

Due to the rapid economy development and booming population, more land is required to develop the systems of infrastructure, residential and commercial buildings, railways and airport. In the land reclamation projects, the layer clay-thin sand model was typically applied as an alternative to the conventional full sand reclamation model as a result of the reduction of usage intensity of natural sand. The thin sand layers have been applied for horizontal drains in reclaimed lands with clay fill and in clay fill embankment [1–4]. These sand layers provide lateral drainage for the soft soil in the consolidation process. Based on the field observation of land reclamation project using the clay-sand systems, Lee et al. [3] indicated that provision of horizontal thin layers of sand between sedimented marine clay layers will make the later settle faster and gain strength more rapidly. The consolidation coefficient estimated using the field settlement of layer clay-sand scheme was larger than that of soft clay from the laboratory consolidation test. Specifically, the consolidation coefficient estimated using the field settlement readings ranges from 7–18 m^2/year, where these values from consolidation test for soft clay ranged from 0.5–4 m^2/year. The field test also presented that the field settlement was smaller obviously than settlement of soft clay calculated from compression data of laboratory consolidation test. With sufficient discharge, the sand seam layers can change the hydraulic gradient of vertical flow of pore water in the soft soil. This results in the complex coupled behavior of the consolidation of clay and horizontal drainage of discharge pore water in the thin sand layers [5]. Therefore, the estimation of effects of sand layer discharge capacity on consolidation behaviors is required in practice.

Moreover, the thin-layered sand seam in soft deposits can be also formed naturally in glacial lakes and postglacial clays, which were often formed with a varved or layered structure due to seasonal variation in deposited particle size [5–7]. In practice engineer, the thin sand seam which is embedded in soft ground can be identified by Piezocone test or using sampler [8]. The piezocone penetration test (CPTu) can detect the sand same based on the results obtained from this test. Some characteristics of thin sand seam embedded in soft clay from CPTu test is as increase of cone resistance and decreases of friction ratio and pore water pressure, can help us to evaluate the thickness of those sand seams [8].

Generally, sand seam embedded in soft clay layer may affect consolidation settlement. In an ordinary soil exploration, a thin sand seam sometimes goes unnoticed. However, if the sand seam allows free drainage, this overlooking causes a great error in settlement-time prediction [9]. Asaoka [9] assumed that the settlement of the layer clay-thin sand seam was equal to total settlement of each clay layer. The average degree of consolidation can calculate simply by average mathematical procedure. However, this is just simple estimation in engineering practice, because consolidation rate and deformation of soft clay with embedded sand seams depends on hydraulic conductivity, stiffness and thickness of those thin sand layers. Therefore, these effects should be considered to predict consolidation behavior of sand seam embedded in soft deposits.

Nowadays, the prefabricated vertical drains (PVDs) are typically applied in soft soil improvement in the land reclamation projects with soft soil. PVDs were typically used to accelerate the consolidation phase for the soil improvement. In the combination of PVDs and horizontal drains (i.e., thin sand seam, prefabricated horizontal drains), the role of horizontal drains is to discharge the pore water in soft soil to vertical drains and the pore water can then squeeze out [10]. Moreover, as thin sand seam layers are deposited naturally in soft soil such as marine clay. Generally, the horizontal drains in soft ground require some means to take the collected water out. Therefore, a combination of PVDs and horizontal drains is a favorable condition for increasing consolidation process in soft deposits.

The prediction of consolidation settlement behavior of PVD-improved soft deposits is still difficult and challenging problem in geotechnical engineering. Moreover, the consolidation settlement behavior of PVD-installed soft deposits is affected by many factors [7]. Therefore, performance of vertical and horizontal drain systems (e.g., thin sand layers) in soft deposits has to be investigated through the experimental and field tests. Although the layered clay-thin sand model of land reclamation has been successfully tested in a small field trial conducted at Palau Tekong Basar [3], the experimental test with the number of thin sand layers have not been attended. In the previous studies [7, 11], the experimental test of PVD-improved soft deposit consolidation was performed on a single stage to investigate the effects of factors on behavior of soil consolidation process. These parameters, such as smear zone, discharge capacity, non-Darcian flow, artesian pressure, was then determined by the back analysis approach. Deng et al. [11] carried out the laboratory model tests for soft soil deposits with and without PVD to consider the consolidation and long-term performance of PVDs. The settlement consolidation behavior of soft deposits and excess pore water pressure were then estimated using a general back-analysis method. When subsoils are a layered inhomogeneous medium as the layered clay-thin sand systems, it is very difficult to develop analytical solutions for its consolidation behavior. Thus, the experimental investigation of consolidation settlement behavior of the layered clay-thin sand systems should be performed.

The aim of this paper is to carry out a series of consolidation tests of the layered clay-thin sand systems to investigate the effects of thin sand layer on the consolidation behavior. Three consolidation tests of the soil column with thin sand seam are performed, in which the one and two of thin sand layer is embedded in first and second column test, respectively. The another one is carried out without thin sand layer.

2 Experimental Test

2.1 Test Program

In this test program, three acrylic columns with the same dimensions were designed for the experimental tests. This is convenient to compare the consolidation behavior of soft deposits. The cases of experiment test are design as follows: Case 1 without thin sand layer; Case 2 and Case 3 with one and two of thin sand layer, respectively. Figure 1 presents a test set-up using a large one-dimensional (1-D) column equipment. The inside diameter of the columns was 0.16 m, and the length of the columns was 0.5 m. Because of high stiffness of acrylic columns, it was ensured that the horizontal deformation was fixed to create one dimension (1-D) deformation model. Soil layers consisted of top sand with 0.05 m thick and soft clay with 0.45 m thick. The soft soils were poured to bottom of column; therefore, the drainage boundary at bottom of column is impervious. The top sand layer was to provide a drainage boundary of consolidation model. The thin sand seam layer with 0.01 m thick was embedded in soft soils. The soft soil and sand layers were separated by filter papers, which can prevent intrusion of sand into soft soil. In this experiment, the external load is a dead load system which was made by plate cuprum. Settlement was measured by a vertical displacement sensor (LVDT) at the top of the loading system.

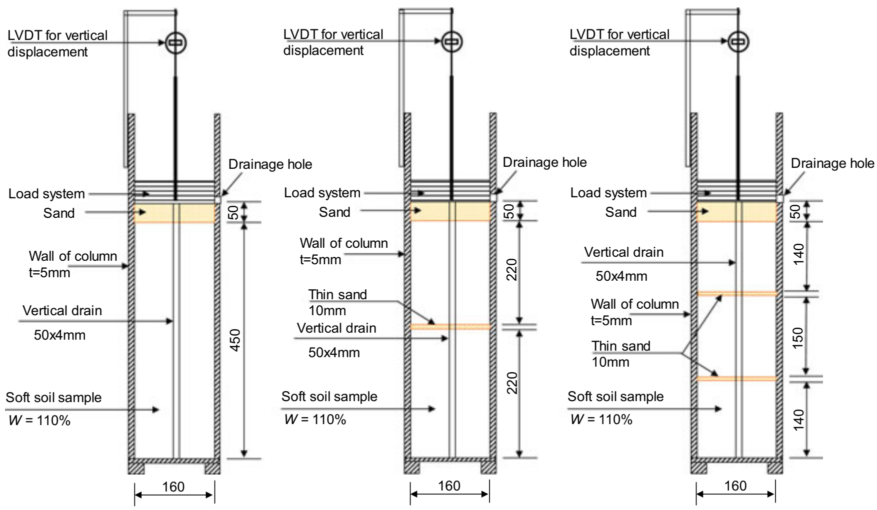

Fig. 1 Layered soft soil-thin sand model: **a** without sand seam; **b** with one sand seam layer and **c** with two sand seam layers (Unit: mm)

Table 1 Geotechnical characteristics of the soft soil using in the experimental test

Properties	Symbol/unit	Values
Field water content	%	88.3
Void ratio	e_0	2.369
Unit weigh	kN/m^3	14.5
Specific gravity	G_s	2.59
Atterberg limit	*LL (%)*	73.4
	PL (%)	45.4
	PI	28

2.2 Materials Using in the Experimental Tests

The soft soil samples used in this experimental test were taken from a depth of 3–5 m from the Kenh 2 bridge at Km 18 + 850, Ho Chi Minh City 3rd Ring Road project, Vietnam. The geotechnical properties of the soft clay samples are presented in Table 1. Because the soft soil samples contained many crushed shell fragments, the soft clay was prepared as homogeneous clay. After preparation, the water content of the soft soil using in the experimental tests was set at 110%. The sand material was applied as a drainage material. It was placed above the soft clay layer. This sand material had a unit weight of 20 kN/m^3 and hydraulic conductivity of 1 m/day. The sand passed through a No. 4 (4.75 mm). This means that the grain-size limit of sand is 4.75 mm. The prefabricated vertical drains used in this study were of the harmonica type with the actual size of 100 mm wide and 4 mm thick. However, the diameter of test column is relatively small. Therefore, the original size of PVD was reduced down to the used size with 50 mm wide, 4 mm thick, and 0.5 m long for each column test.

2.3 Method and Procedure of Test

After setting up the necessary apparatus of test program, the soft soil and sand material were poured sequentially into the test columns. In the first step, the soft soils were filled carefully into the test column using a 0.1 m diameter tube. To reduce any air trapped during pouring process, the lower end of the tube should be immersed in the soft soils. After the soft soil had been placed in the column, the prefabricated vertical drains were installed in the columns center with a small-diameter rod of high stiffness. The top sand layer with 50 mm thick was then poured on top of the clay layer. Before carrying out the 1-D consolidation test for soil columns, the period with 2 weeks were given to wait for self-weight consolidation of the prepared soft soil. Three soil columns with the same conditions except existing the thin sand layer for Case 2 and Case 3. For Case 2, one of thin sand layer was embedded at middle of soft soil layer. For Case 3, two of thin sand layers were embedded in the soft soil layer, as shown in Fig. 1. The filter papers were used to prevent intrusion of sand into soft soil. Three step loadings were applied: 1.492, 2.984, and 4.476 kPa. These loading values are used to ensure that the hydraulic gradients in the experimental test always less than 1. This is due to the initial discharge capacity of PVD was performed under hydraulic gradients of 1 [12]. The duration of consolidation process was 7 days for the first and second loading phases, and 20 days for the third phase. This ensures that the consolidation settlement process of soft soil in columns can completely occurred. During the experimental tests, the settlement data was observed by LVDT. After consolidation test, the water contents of soft soil were also investigated.

3 Experimental Results and Discussion

In the soft soil improvement engineering, the settlement is an important factor to investigate in consolidation characteristics in soft soil deposits. In this study, the settlement results were measured by the LVDT during consolidation. The settlement due to the self-weight consolidation settlement before loading phases was neglected in the observation process. Moreover, the compression properties of sand layers due to external loading were neglected. This means that the observed results of settlement in experimental tests were just considered for soft soil layers. Figure 2 shows the variation in the measured results of settlement of soft soil in the three cases. According to these experimental results, the observed settlement of soft soil without sand seam layer (Case 1) was larger than that with existence of thin sand seam layers (i.e., Case 2, 3). The final settlement in Case 1, Case 2 and Case 3 was 10.25 cm, 10 cm and 9.75 cm, respectively. The experimental results show that the long-term settlement of soft soil without the sand seam layer was larger than that of soft soil with sand seam layer because the thin sand same layers contributed to the increase of foundation stiffness. Generally, these results are completely consistent with the previous studies [3, 5]; however, the rate of consolidation of the subsoils depend on the drainage efficiency provided by the sand layers. Moreover, the settlement rate of soft soil with sand seam layers in early stage is faster than that without sand seam layer. It could be explained that the thin sand layer can play a role as drainage boundary in soft soil; forcedly, this depend on the characteristics of thickness and hydraulic conductivity of thin sand layers which will be discussed in next study.

4 Summary and Conclusion

This paper presents a series of experimental tests of the layered clay-thin sand systems to investigate the effects of thin sand layers on the consolidation settlement behavior of soft soil deposits. The results obtained from the experimental test show that the rate of consolidation settlement (vertical deformation) of vertical drain-installed soft soil deposits with the thin sand layers is faster than that of the case without sand seam,

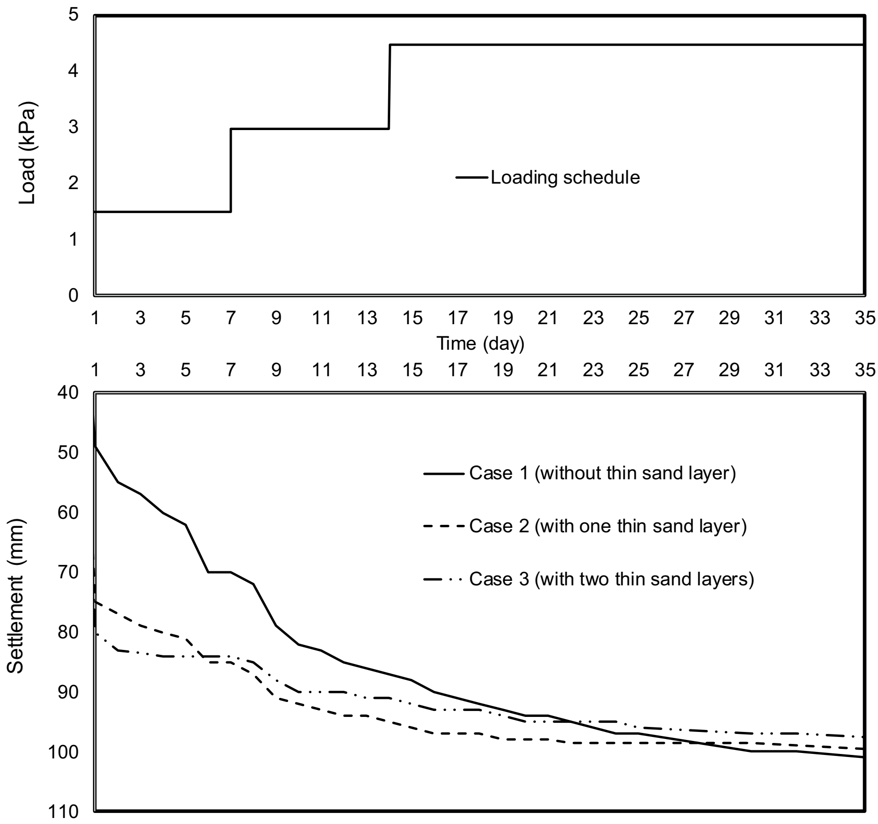

Fig. 2 Loading schedule and observed data of settlement during consolidation process

because the thin sand layers can provide a shorter drainage path for consolidation of the soft soil. The stiffness of soft soil ground is improved and increased due to the existence of thin sand layers. Therefore, the final settlement of vertical drain-installed soft soil in the cases with thin sand layers is reduced, comparing with the case without sand seam.

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