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ORIGINAL PAPER

Radial Consolidation of Soft Soils in Vietnam's Red River Delta: Effect of Drain Diameter on Undisturbed and Remolded Samples

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Abstract Given the increasing demand for soft soil improvement in Red River Delta of Vietnam in the past decade, this study is dedicated to characterizing radial consolidation behaviour of clayey soils in the delta, while varying drain size in the radial consolidation test. Undisturbed soil samples were collected from 3 different sites and subjected to a series of radial and vertical consolidation tests. The central drain diameter in radial consolidation test is varied from 12 to 28 mm, corresponding to the drain spacing ratio n changing from 5.17 to 2.21, to investigate the influence of drainage length on the interpreted outcomes. The alteration of consolidation parameters induced by soil remolding is also studied by comparing the test results of undisturbed and remolded soils. The test results indicate that smaller drain diameter (i.e., larger drainage length) results in larger coefficient of radial consolidation (c_r), for example, c_r increases by a factor of 2 when the drain size varies from 28 mm ($n = 2.21$) to 20 mm ($n = 3.1$). However, when $n > 3.1$, the influence of drainage length on the value of c_r decreases apparently, despite the applied pressure rising from 25 to 800 kPa. New correlations describing the relationship between the value of c_r and n are proposed. On the other hand, soil remolding can cause permeability and coefficient of consolidation to decrease by a factor of 2 to 10. The soil parameters determined from this study are used to implement finite element analysis, resulting in acceptable accuracy of settlement prediction, thus considerable values to practical design of soft soil improvement by PVDs in Red River Delta.

Keywords Prefabricated vertical drains (PVDs) · Soft soil · Red River Delta · Radial consolidation · Drain diameter

Abbreviations

A_c	Activity of clayey soil
a_v	Coefficient of compressibility
C_c	Compression index
C_k	Permeability change index
C_r	Recompression index
c_r	Coefficient of radial consolidation
c_{ref}	Reference cohesion
C_s	Swelling index
c_v	Coefficient of vertical consolidation
CD	Central drain
CF	Clay fraction
D_e	Diameter of soil specimen
D_w	Diameter of the central drain

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e_0	Initial void ratio
e	Void ratio
H	Height of soil element
I_c	Soil behavior type index
k_r	Coefficient of radial permeability
k_v	Coefficient of vertical permeability
LL	Liquid limit
m_v	Coefficient of volume change
n	Drain spacing ratio
n_d	Number of data point
OCR	Overconsolidation ratio
p	Applied pressure
PI	Plasticity index
PL	Plastic limit
POP	Pre-overburden pressure
$PVDs$	Prefabricated vertical drains
q_t	Corrected cone tip resistance
RC	Radial consolidation
S	Settlement of soil specimen
SPT	Standard penetration test
t	Consolidation time
t_{90}	Consolidation time at $U_r = 90\%$
T_r	Time factor
$T_{r,90}$	Time factor at $U_r = 90\%$
u_0	Initial pore water pressure
$\overline{u}$	Average pore water pressure
U_r	Average consolidation degree
VD	Vertical drainage
W_n	Water content
z	Depth of soil sample
α	Ratio of $c_{r,CD12}$ (or $c_{r,CD20}$) to $c_{r,CD28}$
β	Ratio of c_r to c_v
γ	Unit weight of soil
σ'_p	Preconsolidation pressure
ϕ'	Effective friction angle

1 Introduction

The Red River Delta (also known as "Song Hong" Delta), the second largest delta besides the Mekong River Delta in Vietnam, plays a significant role in the economic growth of the country. In recent years, infrastructure for manufacture, transportation and energy have been developed extensively in this delta. The formation of this delta began around 8000–9000 years ago (Holocene Epoch) with the geological features predominantly influenced by the Red River activities and marine processes (Tanabe et al. 2006). Nearer to the coastlines, the geological formation transits from fluvial- to wave and tide-dominated patterns that cause different characteristics in soil fabric and minerals, thus widely varying geotechnical properties. The predominance of alluvial deposits that are transported by the Red River over the years resulted in considerable soft soils, giving significant challenges to geotechnical activities in this delta. For example, the thickness of soft to very soft soils (standard penetration test SPT N < 10) can vary from 10 to 20 m with. The soils include majority of clay and silt with high values of void ratio and compressibility that can lead to substantial settlement under consolidation. Nevertheless, very few studies have been carried out to characterize and compare geotechnical properties, especially consolidation properties, across different locations in the delta.

Soil consolidation induced by prefabricated vertical drains (PVDs) in combination with embankment and vacuum preloading has been applied widely in many countries, especially for soft soil in alluvial and coastal regions such as China, Vietnam, Indonesia, Malaysia and Thailand (Bergado et al. 2002; Kuganeswaran et al. 2021; Lam et al. 2015; Nguyen and Indraratna 2023). In the Red River Delta for the past decade alone, there have been more than a dozen of different ground improvement projects such as Thai Binh Thermal Power plants (2011–2012), and Lach Huyen Port (2022–2023) where PVDs have been effectively combined with vacuum preloading. In this method, the lack of standardized testing methods to determine the coefficient of radial consolidation c_r has caused considerable confusions and inaccurate predictions in practical design and field investigation. In the laboratory, this coefficient can be determined from consolidation test with radial drainage (RC). The test may be carried out by using the conventional incemental loading (IL) method similar to standard vertical consolidation (ASTM D2435 2011) or the constant rate of strain (CRS) method (Seah et al. 2004; Yune and Chung 2005). The CRS method is more advantegeous than the IL method since it is capable of taking into acount of different strain rates and measuring excess pore water pressure. However, the CRS is still a complex and expensive method for many laboratories commpared to the the IL method. In this study, the IL method was adopted.

Figure 1 shows a typical configuration of the RC test where the excess pore water pressure (EPWP)

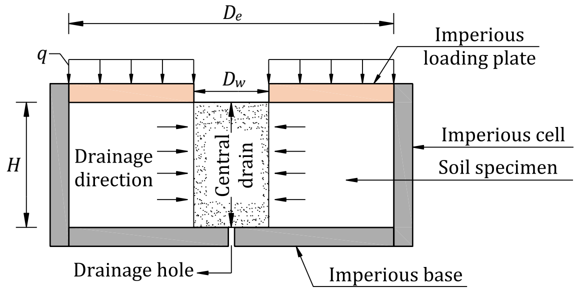


Fig. 1 Typical configuration of radial consolidation (RC) test using a central drain (CD) (modified after Head and Epps, 2014)

dissipates through a central drain (CD) under the IL method. This configuration matches perfectly theoretical consideration of radial consolidation (Barron 1948; Hansbo 1979; Indraratna et al. 2016), which is why the test is used widely to determine the coefficient of radial consolidation. Nevertheless, when comparing with real-life conditions of PVD-treated soil, there are several gaps, for example the difference in boundary condition and geometric parameters between experimental model and the field. Moreover, while the experimental test assumes a perfect radial drainage, soil consolidation induced by PVDs in the field is often governed by both vertical and radial drainage.

Under this test configuration (Fig. 1) and assumptions of no smear and well resistance effects, the average degree of consolidation (U_r) is expressed as follows (Hansbo 1979; Indraratna et al. 2016):

$$U_r = 1 - \frac{\bar{u}}{u_0} = 1 - \exp\left(\frac{-8T_r}{F(n)}\right) \quad (1)$$

where u_0 = initial pore water pressure at time $t = 0$; $\bar{u}$ = average pore water pressure over the area of soil specimen at time t; T_r = the time factor, $T_r = c_r t / D_e^2$; $F(n) = n^2 \ln(n)/(n^2 - 1)$—$(3n^2 - 1)/4n^2$ with $n = D_e/D_w$; D_e and D_w = diameters of the soil specimen and of the central drain, respectively. Unlike the conventional 1D consolidation test with vertical drainage (VD) (ASTM D2435 2011), the RC test with a CD has not been standardized in any systems.

From the definition of T_r, at any time t, the coefficient of radial consolidation (c_r) can be calculated as follows.

$$c_r = \frac{T_r D_e^2}{t} \quad (2)$$

This equation is extensively applied to determine c_r from the time – settlement curve of a CD test by using different methods, which will be discussed later. However, it is noteworthy that previous methods, e.g., Robinson (1997), applying Eq. (2) assumed that c_r is a constant regardless of n value. Some studies (Shields and Rowe 1965; Sridhar et al. 2018) examined the influence of the drain diameter on c_r and found that c_r decreases with larger drain diameter. However, major limitations from past studies are that: (*i*) remolded samples were used in majority of past studies that did not reflect natural structure of undisturbed soil; (*ii*) limited number of tests did not allow a trend of c_r—n relationship to be determined clearly; and (*iii*) there was lack of rigorous explanation on why c_r decreases with increasing drain diameters. Past studies (Guglielmi et al. 2024; Liu and Carter 2002) have shown that changing soil structure (fabric) can lead to significant variation in geotechnical properties. For example, consolidated soil specimens were found to have smaller permeability and coefficient of consolidation compared to compacted specimens, despite having the same void ratio (Silva et al. 2024). Understanding how consolidation parameters can change with undisturbed and reconstituted soils thus becomes important.

In view of the above, this study aims to improve understanding of consolidation characteristics of soft soils in Red River Delta with special reference to PVD-assisted ground improvement techniques. For this, undisturbed soils samples were collected at three different locations representing varying geological conditions in the Red River Delta and then subjected to a series of RC tests. In these tests, effect of the drain diameter (D_w and the drain spacing ratio n) on the test results of undisturbed soils was considered. Moreover, how soil remolding (i.e., soil disturbance), which is commonly used to prepare test specimens in previous studies, can affect the values of hydraulic conductivity and consolidation parameters is explored. The experimental results are also compared with the numerical predictions that further reinforces the findings and broadens practical implications. The outcomes from this study significantly advance the practice of radial consolidation test and selection of soil parameters for simulation in practical designs.

2 Site and Laboratory Investigations

2.1 Site Location and Soil Sampling

Some attempts (Nguyen and Khin 2023; Phuc and Giao 2020) have been made to characterize geotechnical properties of clayey soils in the Red River Delta to assist ground improvement design and construction. However, they are usually carried out for individual locations without correlation among different test results. In our current study, site investigation and soil sampling were implemented in 3 distinct different locations (Fig. 2), i.e., Berths 5&6 of Lach Huyen (LH) Port (Hai Phong City); Bao Minh (BM) Industrial Zone (Nam Dinh province); and Lai Cach (LC) Industrial Zone (Hai Duong province), where various PVD-assisted ground improvements have been implemented in the past decade. As shown in Fig. 2, the LC and BM sites are in the inner delta, while the LH site is in the northeast coastal area of the delta. The soils at LC and BM sites are therefore heavily influenced by fluvial activities, whereas

Fig. 2 Location of soil sampling sites in Red River Delta

LH soils are represented for the combined effect of fluvial and coastal processes with the predominance of coastal activities. Undisturbed soil samples were taken at different depths of each location, enabling soils at varying geological conditions and stress history to be captured.

For soil boring and sampling (Fig. 3a), the borehole was advanced by using the rotary wash method with the use of bentonite slurry to stabilize the borehole walls. At the depth of sampling, a thin-walled fixed-piston tube sampler of 1.0 m long and 76 mm in inner diameter was pushed down to collect undisturbed samples. To ensure the constant speed of penetration, a hydraulic motor control was used. Right after the sample tube was retrieved at the ground surface, the tube ends were cleaned and filled with paraffin and then carefully sealed to preserve water content as well as integrity of the soil sample. All the boring and sampling procedures were carried out in accordance with ASTM D1452 (2009) and ASTM D1587 (2009), respectively. When the sampling at the borehole was complete, the sample tubes were immediately transported to the laboratory for soil testing. In addition, CPTu test within 3 m from the soil borehole was also conducted to study soil stratification, classification and interpretations (Fig. 3b).

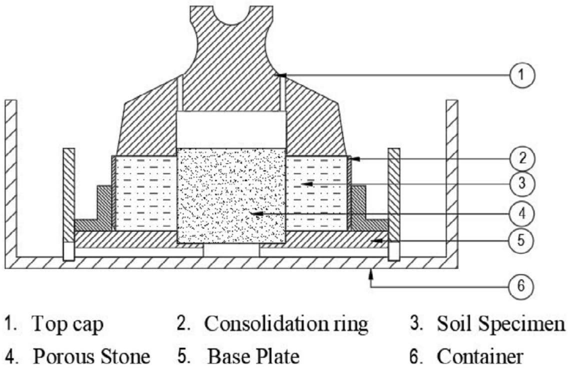
2.2 Laboratory Test Program and Analysis

In practical design of soil improvement under embankment and vacuum preloading, two most common aspects, i.e., compression and consolidation are often considered. The compression characteristics are usually represented via the compression index (C_c), recompression index (C_r), preconsolidation pressure (σ'_p) and coefficient of volume change (m_v). On the other hand, the consolidation behaviour involving the dissipation of excess pore water pressure over time depends mainly on the permeability of soil. To determine these parameters for clayey soils at the study sites, a series of conventional consolidation tests with vertical drainage (VD), i.e., oedometer apparatus (ASTM D2435 2011) and radial consolidation (RC) test using a central drain (CD) were carried out on the collected soil samples (Fig. 4). The diameter of the CD was varied to examine the influence of drain diameter on the test results. In addition, other fundamental properties such as the natural unit weight (γ), water content (W_n), Atterberg's limits and void ratio (e_0) were determined.

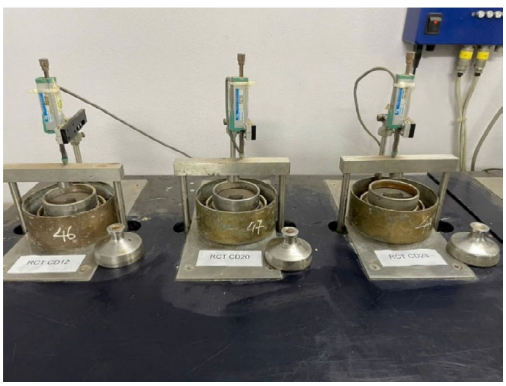
In the laboratory, undisturbed soil samples collected from the field were extruded from the thin-walled tubes and cut into 10 cm long pieces which were all carefully wrapped in plastic membrane and then waxed to preserve water content of the samples. The 10 cm soil piece was divided into 3 equal parts for different purposes, i.e., determining basic soil parameters, CD and VD tests. This ensured that the properties and quality of soil specimens used for CD and VD tests were identical. For each consolidation test, seven loading steps, i.e., 12.5, 25, 50, 100, 200, 400, and 800 kPa were applied on the specimen. The

(a) (b)

Fig. 3 Soil investigation at Lai Cach (LC) site **a** Soil sampling; **b** CPTu test



(a)



(b)

Fig. 4 Radial consolidation test: **a** diagram of CD test with reference to drain diameter of 28 mm (CD28); **b** test equipment with different drain diameters, i.e., CD12, CD20 and CD28

test method B (ASTM D2435 2011) was referred, i.e., the loading step was completed after 100% primary consolidation was achieved by considering the settlement curve. Thus, each loading step was completed in about 3 to 4 h. Table 1 summarizes the tests conducted in this study.

The RC test was carried out by modifying the standard 1D consolidation cell to house a central porous stone as shown in Fig. 4a. The bottom porous stone in the standard cell was replaced by an impervious steel plate, so only radial drainage to the central drain could occur. A central hole of the soil specimen that perfectly fits the diameter of the central drain was made by using a mini thin-walled sampler. The verticality and centricity of the central drain was guaranteed by using a steel top cap (through the consolidation ring) with a central hole to guide the position of the stone. The RC test in this study was carried out with the central porous stone having three different diameters, i.e., $D_w = 12$, 20 and 28 mm, corresponding to $n = 5.17$, 3.10 and 2.21, respectively.

To examine the influence of soil disturbance on the consolidation characteristics, VD and CD tests were also carried out on remolded specimens. From the same soil sample where the undisturbed test specimen was formed, the soil was cut into small pieces and manually mixed to break natural structure of the soil. This process was carried out in a sealed bag and conditional room (humidity and temperature controlled) to minimize change in water content. The remolded soil was then placed into the consolidation cell, while the soil mass was controlled to ensure the test specimen had identical unit weight to the undisturbed specimen. This meant that the remolded and undisturbed specimens had the same initial void ratio before loading, facilitating the assessment of the

Table 1 Summary of consolidation tests carried out in the study

No	Test name	Lach Huyen (LH)		Bao Minh (BM)		Lai Cach (LC)	
		No. of samples		No. of samples		No. of samples	
		Undisturbed	Remolded	Undisturbed	Remolded	Undisturbed	Remolded
1	CD28 ($n = 2.21$)	10	10	8	8	5	5
2	CD20 ($n = 3.10$)	10	10	8	8	5	5
3	CD12 ($n = 5.17$)	10	10	8	8	5	5
4	VD	10	9	8	8	5	5

CD12, CD20, CD28 = central drain (CD) test with $D_w = 12$ mm, 20 mm, and 28 mm, respectively; VD = vertical drainage test (i.e., conventional oedometer test) influence that disturbed soil structure can have on its permeability and consolidation behaviors.

In the literature, various methods have been proposed to determine c_r value from a CD test, for example, the root t method (Berry and Wilkinson 1969), inflection point method (Robinson 1997), non-graphical matching method (Robinson and Allam 1998), log–log method (Robinson 2008), steepest tangent method (Vinod et al. 2010), log t method (Sridhar and Robinson 2011), full-match method (Chung et al. 2018). These methods exploit specific features of the theoretical time factor—consolidation degree (T_r−U_r) curve such as the $T_r^{0.5}$−U_r curve in the range U_r = 20% to 60% to determine c_r at U_r = 90% (root t method); and the maximum slope of U_r − log(T_r) curves at U_r = 63.21% to determine c_r (inflection point method). All these methods assume c_r constant in the range of U_r = 0 to 100% with various values of n, whereas the question of how varying n can affect the value of c_r has not been clarified. However, for real soil samples, especially undisturbed soil samples, different methods are found to yield certain variation in the estimated c_r values, which is because of the unavoidable difference between real and ideal soil conditions (Khin 2022).

In this study, the root t method (Berry and Wilkinson 1969) was adopted for the CD test to determine c_r, similarly to the root t method (ASTM D2435 2011) adopted for determining the coefficient of vertical consolidation (c_v) in the VD test. The two methods were selected because of their sound theoretical bases and popularity. Furthermore, the selection of the two methods can facilitate correlations between c_r and c_v values which are interpreted based on the same concept of calculation.

Figure 5 shows a typical graph of root time – settlement for determining c_r value from the root t method. The procedure of the method can be briefed as follows: (*i*) plot the root time – settlement curve; (*ii*) identify an initial relatively linear portion of the curve and draw a tangent line (i.e., Line AB) to this relatively linear portion; (*iii*) draw a scaled line (i.e., Line AC), which has abscissa of 1.167 times that of the tangent line; (*iv*) determine the abscissa of the intersection point (i.e., Point D) of the scaled line and the root time – settlement curve and this abscissa is regarded as $t_{90}^{0.5}$; (*v*) determine t_{90} and calculate the c_r value at 90% of consolidation as follows.

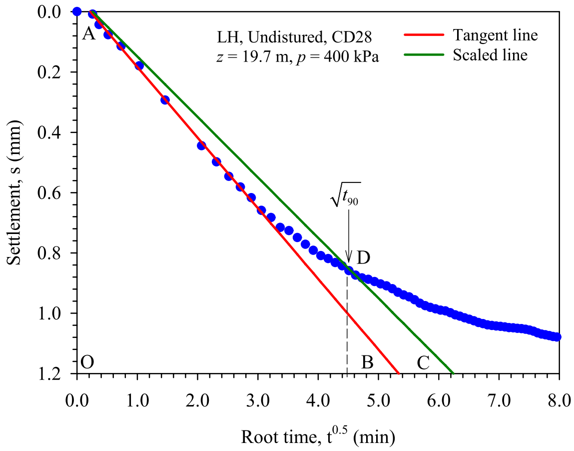


Fig. 5 Root t method applied to consolidation test (CD28) of a LH sample

$$c_r = \frac{T_{r,90} D_e^2}{t_{90}} \tag{3}$$

where $T_{r,90}$ is the time factor at U_r = 90% and this value varies depending on n value (i.e., different drain diameters).

It is noteworthy that the standard procedure of the root t method described above does not specify how to construct a proper tangent line. In fact, the time factor – consolidation degree (T_r – U_r) curve is approximately linear in the range of U_r = 0.2 to 0.6. Considering this basis and applying the analogy, the tangent line (step *ii* above) was constructed by using the following sub-steps: (*a*) the settlement at 100% consolidation (s_{100}) is determined as the intersection of two tangent lines (one through the inflection point and the other through data points after 100% consolidation) and the time – settlement curve; (*b*) once s_{100} is determined, the corrected settlement at 0% consolidation (s_0) can approximately be determined following the procedure recommended in Sridhar and Robinson (2011); (*c*) once s_{100} and s_0 are determined, the settlement at 20% consolidation (s_{20}) and at 60% consolidation (s_{60}) can be determined (i.e., s_{20} = 0.2(s_{100}−s_0) and s_{60} = 0.6(s_{100}−s_0); (*d*) the tangent line can then be drawn to the portion from s_{20} to s_{60}.

3 Results and Discussion

3.1 Geological Features and Soil Profiles of 3 Different Sites in Red River Delta

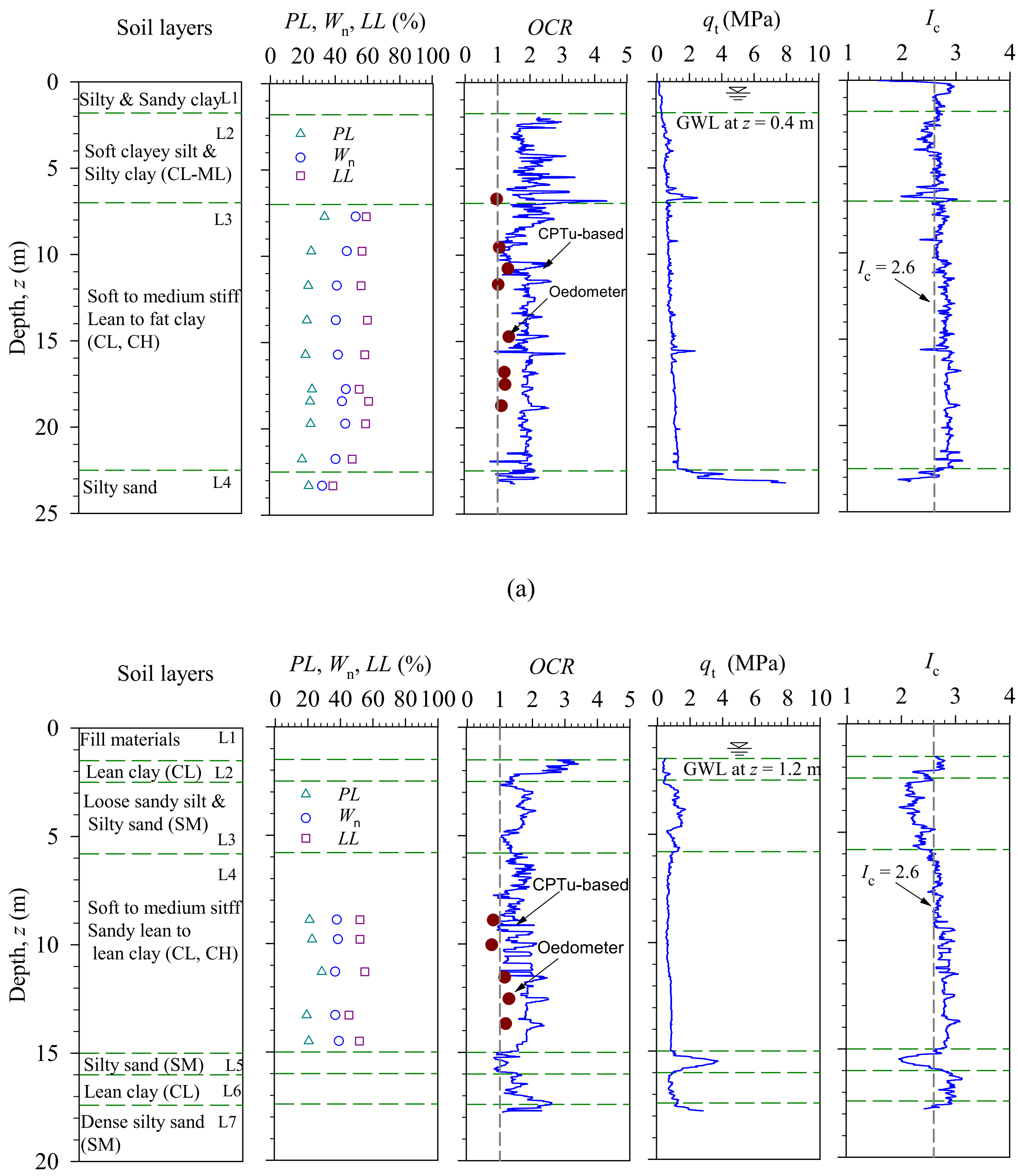
Figure 6 represents stratigraphy of soils in the 3 sites including soil classification according to borehole records and CPTu-based criteria, natural water content (W_n), liquid limit (*LL*) and plastic limit (*PL*), overconsolidation ratio (*OCR*), corrected cone tip resistance (q_t) and soil behavior type index I_c (Robertson 2009). Table 2 shows the average soil properties of the clayey soils at the study sites. It is interesting that BM and LC sites, which are both located away from the coast, have relatively similar soil stratigraphy. As shown in the figures, soft silty clay and clayey to sandy silt layers (CM-ML, SM) are found from the ground surface to the depth of about 6–7 m for these sites, following by soft to medium stiff lean to fat clay (CL, CH) up to 22.5 m at BM site, and soft to medium stiff sandy to lean clay up to 15.0 m at LC site. The soft clay layers have a water content of 40–58% that is relatively near to its liquid limit (around 60%). The corrected cone resistance q_t of clays ≤ 1.0 MPa indicates high to moderate compressibility, even at a large depth of 22 m at BM site. Based on C_c value (Table 2), the clay at BM can be classified as moderate compressibility ($0.2 \leq C_c \leq 0.4$), whereas it is highly compressible ($C_c \geq 0.4$) for the LC soil (Nguyen and Khin 2023). These clayey soils are normally consolidated (NC) to slightly overconsolidated (OC) with the CPTu-based OCR value changing from 1.0 to 1.8, which agreed well with the OCR values determined from lab tests. The very similar geotechnical properties of clays reflect the similar geological activities that these two sites experienced in their history.

On the other hand, LH site has rather distinct soil profile as it is located at the estuarine area of Cam and Chanh rivers, where sediments from the rivers and ocean interact and settle down. It is noteworthy that the seabed elevation in the port area before the construction varied from 2.0 to 5.0 m below the chart datum (.i.e., the lowest astronomical tide), while the soil profile shown in Fig. 6c was obtained from sampling work and CPTu test carried out around 1 year after a new 6 m thick layer (Layer L1) of dredged sand was filled. The major clay layers at the site are soft fat clay (Layer L2) and soft to medium stiff fat clay (Layer L4) up to about 21.5 m depth, which are interbedded by a thin silty sand (layer L3). Both clay layers at the site can be classified as high compressibility ($C_c > 0.4$). A comparison of basic properties at the three sites revealed that: (*i*) while the fines content (i.e., % of particles < 0.075 mm) of clay layers at the three sites are relatively equal, the unit weight (γ) and water content (W_n) of layers L2 and L4 at LH site are respectively smaller and larger than those of clay layers at LC and BH sites; (*ii*) the q_t value of layer L2 at LH site is distinctively smaller that of clay layers at similar depths (i.e., from 6.0 to12.0 m) at LC and BM sites, whereas the q_t value of layer L4 at LH site is relatively equal to that of clay layers at similar depths (14 to 21 m) at LC and BM sites; (*iii*) the soil behavior type index (I_c) value of layers L2 and L4 at LH site is distinctively larger than that of clay layer at LC and BM site. These features indicate that the clay layers at LH site are younger and have higher compressibility than that at LC and BM sites.

Figure 7 shows typical time–settlement curves resulted from consolidation test of soil samples collected at similar depths (8.9–9.5 m) at the three sites under a normal pressure of 100 kPa. At this depth, the same soil classification, i.e., soft lean to fat clay is found across different locations (Fig. 6). The results show significant differences in the compression behaviour among the 3 soils. LH soil exhibits the largest settlement, followed by the LC and BM soils. This means that the soil at LH has considerably larger coefficients of volume change (m_v) and consolidation. This result in fact corroborates the earlier discussion based on CPT test data. It is noted that the OCR of these soils are relatively the same.

3.2 Influence of Drain Diameter on the Coefficient of Radial Consolidation

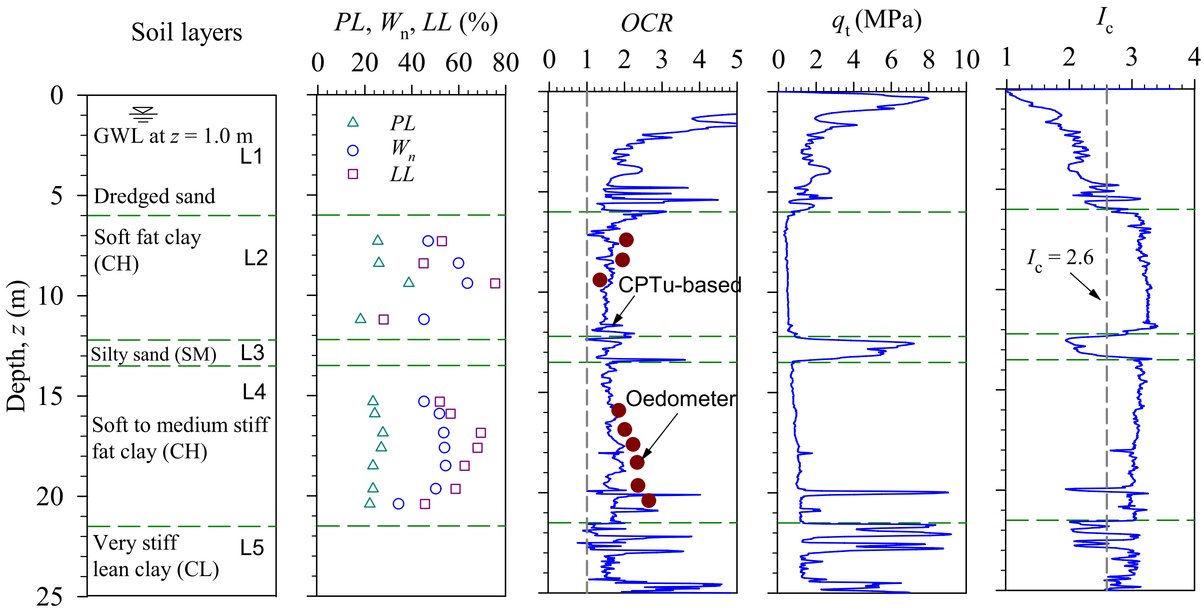
The variation of the coefficient of radial consolidation (c_r) with different drain diameters (i.e., *n* varies from 2.2 to 5.17) and applied pressures are shown in Fig. 8. In this demonstration, the results for undisturbed and remolded soils at representative depths across 3 different locations are included for comparison. In overall, the results show that the larger the *n* value, the larger the value of c_r. When *n* increases from 2.2 to 3.1, c_r of BM undisturbed soil increases substantially, for example, it changes almost double from 0.055 m^2/day to more than 0.11 m^2/day under 100 kPa pressure



(a)

(b)

Fig. 6 Soil profile at the test sites: **a** Bao Minh (BM); **b** Lai Cach (LC); **c** Lach Huyen (LH)



(c)

Fig. 6 (continued)

Table 2 Average soil properties of clay layers at the study sites

Site	Depth	γ	W_n	e_0	LL	PL	PI	CF	A_c	C_c	OCR	Soil name
	(m)	(kN/m^3)	(%)		(%)	(%)	(%)	(%)				
LH	6.0–12.0	16.8	55.8	1.45	65.5	32.1	33.4	20.5	1.64	0.42	1.78	Fat clay (CH)
LH	13.5–21.5	17.4	49.7	1.30	60.2	24.6	35.7	21.1	1.70	0.52	2.09	Fat clay (CH)
BM	7.0–22.5	17.5	43.2	1.20	48.4	25	23.4	35.3	0.68	0.28	1.16	Lean to fat clay (CL, CH)
LC	6.0–15.0	17.4	46.9	1.27	46.9	22.3	24.5	41.4	0.60	0.53	1.03	Sandy lean to lean clay (CL, CH)

LH Lach Huyen, *BM* Bao Minh, *LC* Lai Cach

(Fig. 8a). However, the change becomes insignificant when n rises from 3.1 to 5.17. This indicates a certain value of n around 3 that any further increase (i.e., larger diameter of drain) does not affect the value of c_r. Also, it is understandable that increasing the applied pressure results in larger settlement of soil, thus higher value of c_r. Calculation of consolidation must be considered with respect to the range of load that is applied through embankment and surcharge. Note from the figure that the variation of c_r at some loading steps (e.g., at $p = 800$ kPa on BM remolded specimen (Fig. 8a), $p = 400$ kPa on LH remolded specimen (Fig. 8c)) does not totally fit to the general trend discussed above. This might be attributed to imperfections in test performance and inhomogeneity of soil specimens.

The results show that remolding has changed the value of c_r substantially. For BM soil, c_r decreases by a factor of 2 to 3 when comparing undisturbed and remolded samples of soil at the same depth. For example, for $n = 3.1$ and normal pressure $p = 100$ kPa, c_r is about 0.11 m^2/day for undisturbed soil, but it drops to around 0.045 m^2/day for remolded soil for BM. For LC soil, the influence of remolding becomes more severe. The value of c_r decreases by a factor of 5 to 10 when soil is remolded and loses its structure. LH soil exhibits the same reduction rate to what BM soil experiences when subjected to remolding.

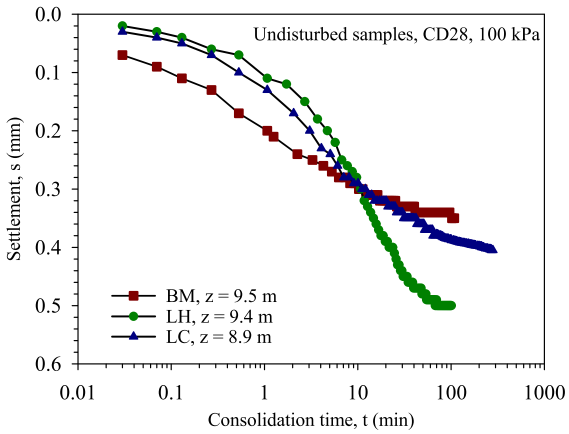


Fig. 7 Consolidation curves of soft clays at 8.9–9.5 m in the 3 investigated sites: Bao Minh (BH), Lai Cach (LC) and Lach Huyen (LH)

However, the c_r of LH undisturbed soil is considerably smaller than BM and LC soils. In fact, BM soil has the largest value of c_r which is almost double and 4–5 times larger compared to that of LC and LH soils, respectively.

Figure 9 shows an example of settlement curves with time when different drain diameters, 12, 20 and 28 mm are used for an LC undisturbed soil sample. The results show clearly that, at the same time in the primary consolidation, the test with larger drain diameter results in greater settlement. For example, at $t = 10$ min, the test with $D_w = 12$ mm ($n = 5.17$) resulted in a settlement of 0.29 mm, whereas the test with $D_w = 28$ mm ($n = 2.2$) resulted in a settlement of 0.52 mm. This is because larger drain diameter resulted in shorter drainage length, making faster dissipation of excess pore water pressure and thus larger settlement. As n increases (i.e., the drainage length increases), both $T_{r,90}$ and t_{90} also increase but the increment rate of $T_{r,90}$ is large than that of t_{90}, leading to the increase in $T_{r,90}/t_{90}$ ratio. Since D_e is constant for different drain diameters, the c_r calculated by Eq. (3) increases with the increase in n as typically expressed in Fig. 8. Figure 9 shows that the consolidation curves from different drain diameters under the same applied pressure do not reach an identical final settlement. This can be attributed to the fact that different tests, despite having the same soil thickness, were affected by varying permeability and boundary conditions due to different soil-drain contact area, causing slight change in settlement behaviour. Because of this immediate impact on the settlement curve as well as the value of c_r, the lack of consistent testing system and guidelines can lead to significant deviation in the tested results and predicted behaviour of soils treated by PVDs.

The values of c_r obtained from different drain diameters are correlated to each other by using the following equation.

$$c_{r,CD12}\left(or\, c_{r,CD20}\right) = a c_{r,CD28} \tag{4}$$

where α = ratio of $c_{r,CD12}$ (or $c_{r,CD20}$) to $c_{r,CD28}$, while $c_{r,CD12}$, $c_{r,CD20,}$ and $c_{r,CD28}$ are obtained from the RC tests with the drain diameter of 12 mm (CD12), 20 mm (CD20), and 28 mm (CD28), respectively. For convenient comparison, the $c_{r,CD28}$, which is obtained from the largest drain diameter in the series, is taken as the reference value.

As an example, Fig. 10 shows the correlations between $c_{r,CD12}$ and $c_{r,CD28}$ for undisturbed and remolded soils at BM site, where n_d = number of data points taken into analysis. In this analysis, data points from soil samples obtained from depths of 6.8 to 18.8 m (layer L3) and subjected to different applied pressures (p from 25 to 800 kPa) are included to determine a general trend. As the results show, $c_{r,CD12}$ is approximately 1.8 times larger than that $c_{r,CD28}$ for the undisturbed soil, however the ratio decreases to 1.54 for the remolded soil. The proposed empirical equations have acceptable accuracy with the coefficient of determination $R^2 = 0.91$ and 0.98 for undisturbed and remolded soils, respectively.

Table 3 summarizes the values of α and the corresponding R^2 for the three sites. Generally, the value of α changes from 1.21 to 1.80, and from 1.28 to 1.54 for undisturbed and remolded soils when n increases from 2.21 (CD28) to 5.17 (CD12). The value of R^2 is larger than 0.9 for all different cases. The results clearly indicate that, for both remolded and undisturbed soil conditions, the smaller the drain diameter (i.e., larger the drainage length), the larger the value of c_r. This signifies that the radial drainage length influences the interpreted c_r significantly. This might draw serious attention to the fact that past theoretical derivations of radial consolidation often assumed constant c_r irrespective of varying n. Furthermore, as there is currently no agreement over which configuration and drain diameter of radial consolidation test should be used, the current results provide useful

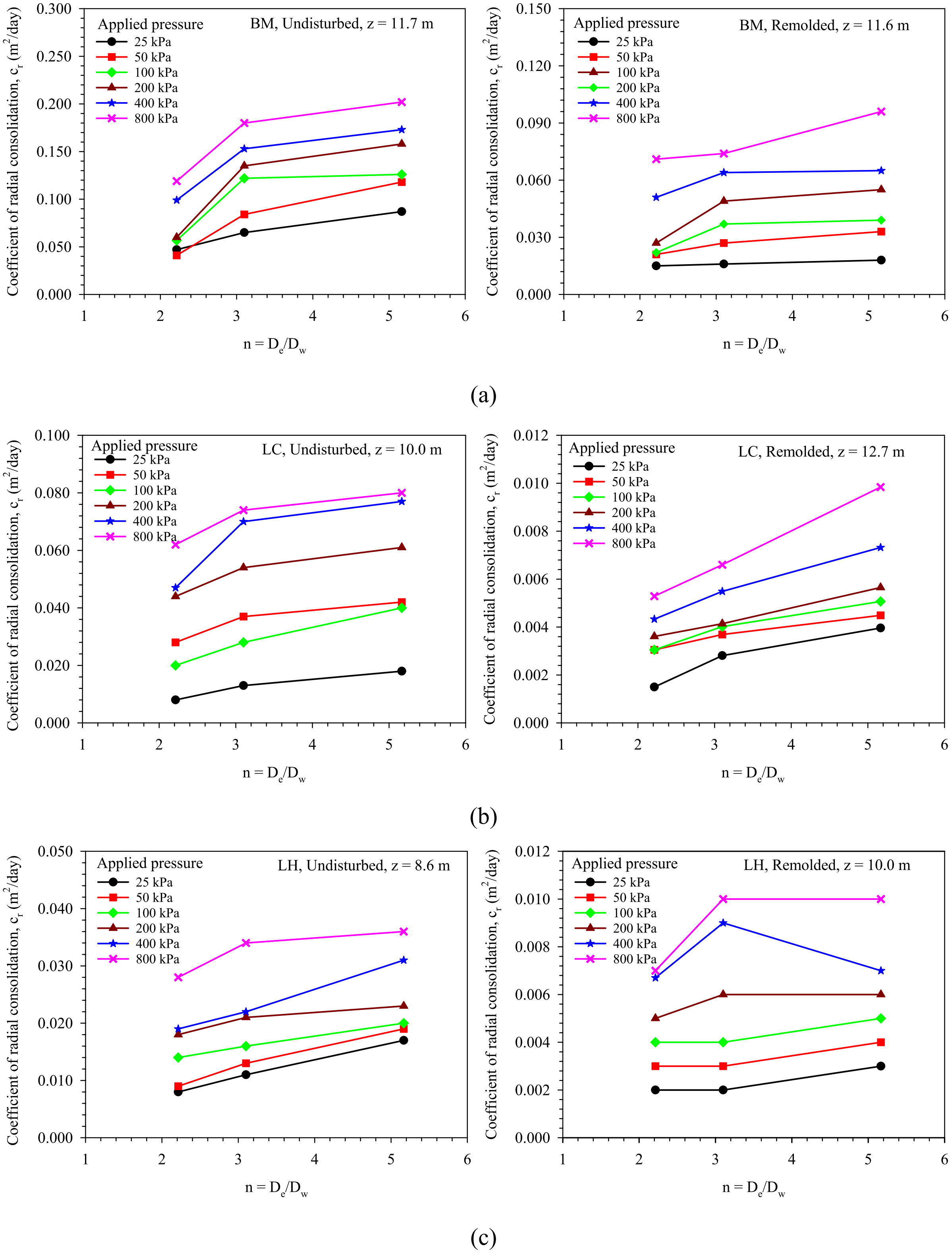


Fig. 8 Variation of c_r with n and applied pressure for: **a** BM site; **b** LC site; **c** LH site

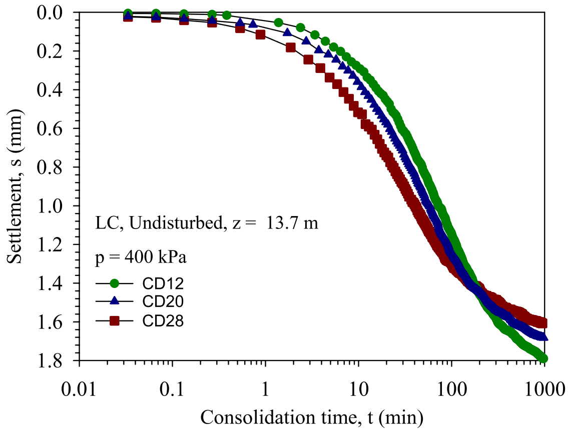


Fig. 9 Settlement developed with time when using different drain diameters, CD = 12, 20 and 28 mm, example with a LC undisturbed soil sample

correlations between different drain diameter systems, giving valuable support to practical design.

Similar to the correlation between c_r values obtained from different drain diameters (Eq. 4), the correlation between c_r and c_v (Eq. 5) is developed to examine the influence to drain diameters to the ratio of c_r/c_v as follows.

$$c_{r,CD12}\left(or\, c_{r,CD20},\, c_{r,CD28}\right) = \beta c_v \tag{5}$$

where β = ratio of $c_{r,CD12}$ (or $c_{r,CD20}$, $c_{r,CD28}$) to c_v.

Table 4 summarizes the values of β and R^2 for different cases. The results indicate that larger drain diameter (i.e., smaller n value) leads to smaller c_r/c_v ratio and this is applicable to both undisturbed and remolded soil samples. For the undisturbed soil samples from the three sites, the c_r/c_v ratio varies from 3.98 (n = 5.17 at LC) to 1.57 (n = 2.21 at BM). For remolded soil samples, the c_r/c_v ratio is

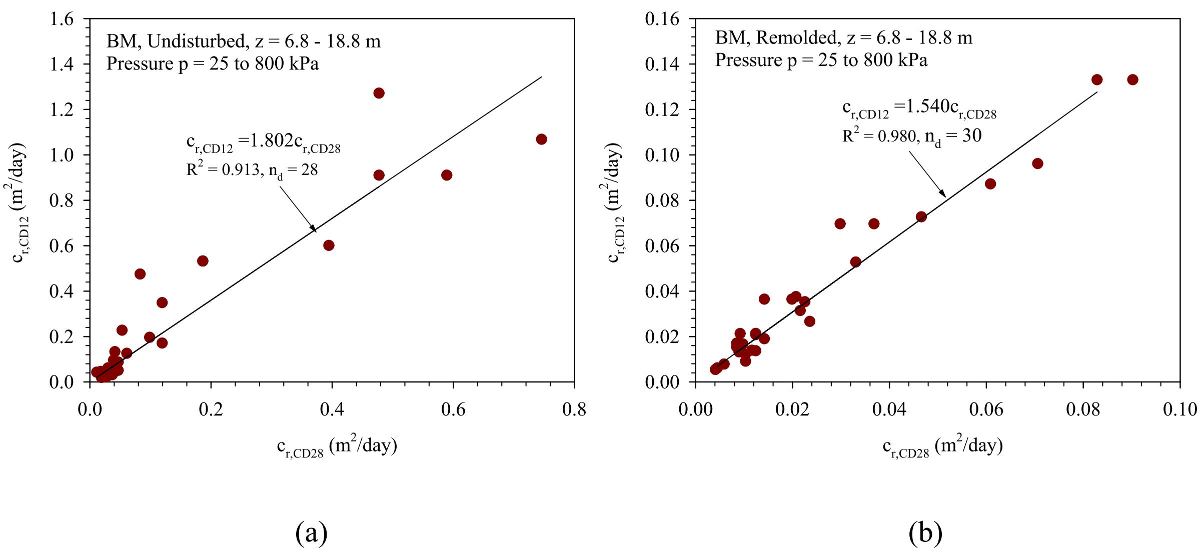


Fig. 10 Correlations of c_r values determined by using drain diameters D_w = 12 mm (CD12) and D_w = 28 mm (CD28) for Bao Minh (BM) site: (a) Undisturbed; (b) Remolded; herein n_d is the number of data points used for analysis

Table 3 Summary of correlation coefficients α

Specimen condition	Correlation	Bao Minh (BM)			Lai Cach (LC)			Lach Huyen (LH)		
		α	R^2	n_d	α	R^2	n_d	α	R^2	n_d
Undisturbed	$c_{r,CD12} = \alpha c_{r,CD28}$	1.802	0.913	28	1.209	0.906	25	1.276	0.912	47
	$c_{r,CD20} = \alpha c_{r,CD28}$	1.436	0.977	21	1.054	0.993	24	1.124	0.977	48
Remolded	$c_{r,CD12} = \alpha c_{r,CD28}$	1.541	0.980	30	1.337	0.988	21	1.278	0.980	54
	$c_{r,CD20} = \alpha c_{r,CD28}$	1.267	0.949	32	1.119	0.993	19	1.060	0.949	55

Table 4 Coefficients of correlations between c_r and c_v

Specimen condition	Correlation	Bao Minh (BM)			Lai Cach (LC)			Lach Huyen (LH)		
		β	R^2	n_d	β	R^2	n_d	β	R^2	n_d
Undisturbed	$c_{r,CD12}=\beta c_v$	3.279	0.8413	16	3.985	0.8392	18	3.029	0.8813	43
	$c_{r,CD20}=\beta c_v$	2.728	0.9466	24	3.547	0.8167	20	2.437	0.889	48
	$c_{r,CD28}=\beta c_v$	2.290	0.8752	19	3.153	0.9186	16	2.196	0.8997	43
Remolded	$c_{r,CD12}=\beta c_v$	2.525	0.8574	34	2.538	0.9621	20	1.830	0.9555	35
	$c_{r,CD20}=\beta c_v$	2.292	0.9000	34	2.006	0.9679	20	1.544	0.9484	52
	$c_{r,CD28}=\beta c_v$	1.569	0.9164	32	1.744	0.9421	20	1.296	0.897	51

slightly smaller than that from the undisturbed soil samples and it varies from 3.28 ($n=5.17$ at BM) to 1.74 ($n=2.21$ at LC). Comparing undisturbed and remolded soils for the same test conditions, the value of β generally decreases by a factor of 1.2 to 1.8 when soil is remolded. Past studies (Indraratna and Redana 1998; Zhao and Zhou 2022) indicate the permeability and coefficient of consolidation of soil in horizontal drainage can be 1.6–5 times greater than those in vertical direction. While the results from this study are well within the previous ranges, it also suggests that the disturbed soils would have smaller gap (smaller value of β) between the consolidation behaviour induced by vertical and radial drainages.

3.3 Influence of Undisturbed and Remolded Condition on Permeability of Soils

Permeability is the core parameter determining consolidation behaviour of soil. In the design of soil consolidation by PVDs, the coefficient of radial permeability (k_r) is one the most crucial parameters that requires significant effort and consideration. Based on the c_r and c_v determined from the consolidation tests, k_r and k_v are determined for each loading step as follows.

$$k_r = \frac{c_r \gamma_w a_v}{1 + e} \tag{6a}$$

$$k_v = \frac{c_v \gamma_w a_v}{1 + e} \tag{6b}$$

where a_v is the coefficient of compressibility, e is the void ratio of the soil specimen at the beginning of

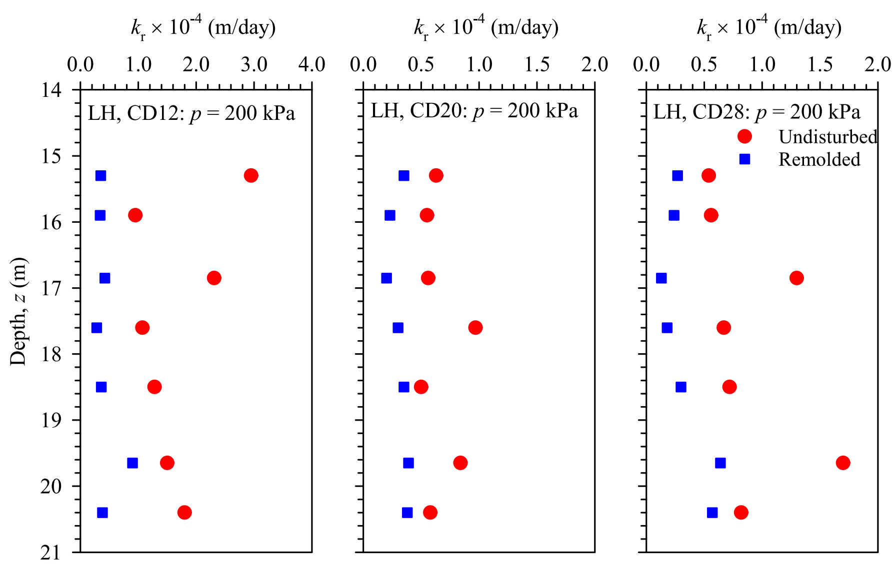


Fig. 11 Coefficient of radial permeability (k_r) of undisturbed and remolded soils at LH site

the examined pressure, γ_w is the unit weight of pore water.

Figure 11 compares k_r of the undisturbed and remolded soils over depth at Lach Huyen (LH) site obtained from an applied pressure of 200 kPa. The results show that k_r decreased significantly by a factor from 1.4 to 6 when the soil was remolded and lost its natural structure. In fact, past laboratory and field investigations (Indraratna and Redana 1998; Zhao and Zhou 2022) often reported a reduction in permeability of soil around 1.6 to 5 times due to smear (soil disturbance due to installation of PVDs), which is in good agreement with the current study.

Similarly, Fig. 12 shows the variation of permeability in vertical direction (k_v) with depth of undisturbed and remolded soils across 3 sites obtained from an applied pressure $p = 200$ kPa. Similar to the $k_{r,undisturbed}/k_{r,remolded}$ ratio, the ratio $k_{v,undisturbed}/k_{v,remolded}$ also depends significantly on the location, i.e., the ratio varies from 1.2 to 2.5 for LH site, 1.8 to 2.7 for LC site, and 2.5 to 9.5 for BM site.

4 Numerical Simulation of Radial Consolidation Tests: Results and Experimental Validation

To enhance understanding of radial consolidation considering different values of n and soil structure destruction, finite element method (FEM) was used to simulate the radial consolidation tests on both undisturbed and remolded specimens. The reliability of the FEM model was first verified by comparing experimental and numerical results, and then the influence of soil remolding on c_r value was numerically investigated. Details of the FEM analysis are described as follows.

4.1 Model Setup and Parameter Selection

In this study, the FEM incorporated in Plaxis 2D software was used to simulate the test. The Soft Soil (SS) model, which has been proved to be well suitable in simulating consolidation behaviour of soft clays (Kuganeswaran et al. 2021; Waheed and Asmael 2024), was selected for the analysis. Table 5 shows the input parameters for the numerical test of CD28 carried out for four typical soil samples: undisturbed and remolded soils at LH and BM sites. Note from the table that the model dimensions (i.e., diameter and height of soil specimen) and soil input parameters such as γ, e_0, C_c, C_s, k_x (k_r) and k_y were identical to those of actual soil samples tested in the lab. The boundaries were set to enable only radial drainage to occur toward the central drain.

The same number of loading stages (6 stages) and consolidation time to experimental tests, i.e., applied pressure from 12.5 to 800 kPa were carried out in numerical simulation. Excess pore water pressure was allowed to dissipate horizontally to the central drain, while the vertical load was applied

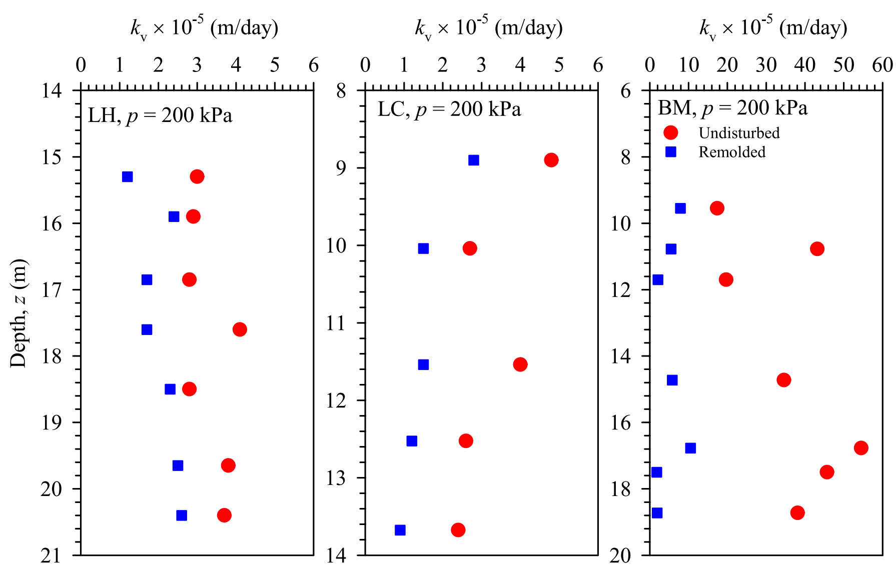


Fig. 12 Coefficient of vertical permeability k_v of undisturbed and remolded soils in Lach Huyen (LH), Lai Cach (LC) and Bao Minh (BM) sites

Table 5 Input parameters of Soft Soil model for the numerical analysis of CD test

Parameter	Unit	LH, CD28 Undisturbed	LH, CD28 Remolded	BM, CD28 Undisturbed	BM, CD28 Remolded
Depth of soil sample, z	m	17.6	17.1	14.7	14.8
Diameter of soil element, D_e	mm	62	62	62	62
Height of soil element, H	mm	20	20	20	20
Unit weight, γ	kN/m^3	18	18	18.3	18.3
Void ratio, e_0	–	1.40	1.43	1.18	1.16
Poisson's ratio, ν_{ur}		0.2	0.2	0.2	0.2
Compression index, C_c	–	0.55	0.30	0.35	0.19
Swelling index, C_s	–	0.055	0.02	0.1	0.02
Reference cohesion, c'_{ref}	kN/m^2	2	2	2	2
Effective friction angle, ϕ'	Degree	30	30	27	27
Coeff. of horizontal permeability, k_x	m/day	11.23×10^{-5}	6.02×10^{-5}	9.80×10^{-4}	1.75×10^{-4}
Coeff. of vertical permeability, k_y	m/day	4.19×10^{-5}	2.2×10^{-5}	4.26×10^{-4}	1.09×10^{-4}
Permeabilty change index, C_k	–	0.35	0.20	0.3	0.2
Over-consolidation ratio, OCR	–	1.0	1.0	1.0	1.0
Pre-overburden pressure, POP	kPa	120.0	0.0	130.0	0.0

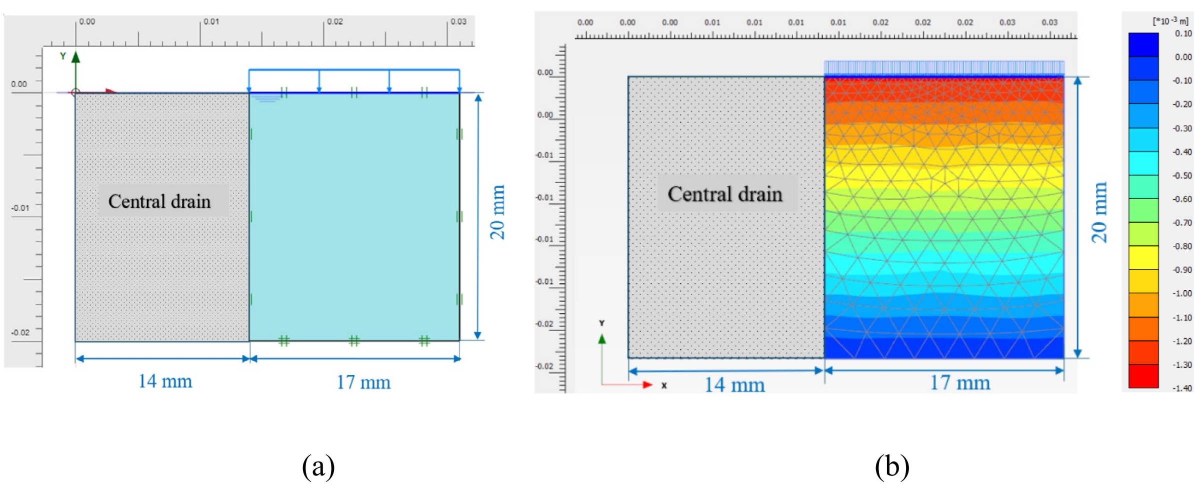


Fig. 13 Numerical model of the CD test, $D_w = 28$ mm for Lach Huyen (LH) soil, depth = 17.6 m: **a** model setup; **b** deformation map of soil at loading step = 800 kPa

on the soil surface (Fig. 13a). Figure 13b shows the consolidated soil domain of the CD numerical test ($D_w = 28$ mm) for LH undisturbed soil specimen under applied pressure of 800 kPa. The deformation profile of the soil under loading is well captured in the numerical analysis with the settlement distributed more in the upper zone.

4.2 Numerical Results and Practical Implications

Figure 14 compares experimental and numerical curves of cumulative settlement over time for 4 different cases, i.e., undisturbed and remolded soils of LH and BM sites. The results show that the cumulative settlement curves from the numerical analysis

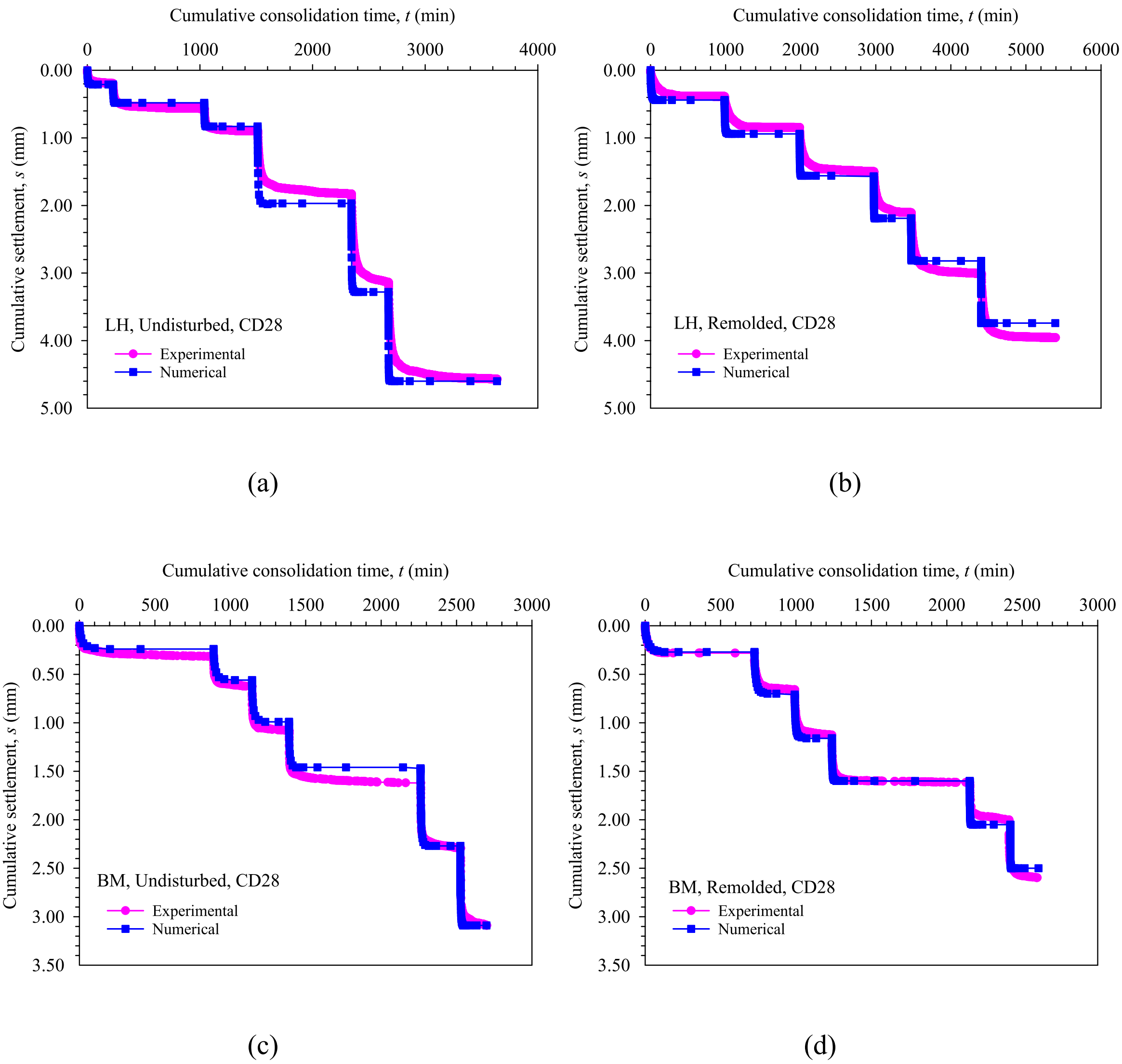


Fig. 14 Numerical results for time-settlement of radial consolidation test with $D_w = 28$ mm: **a** LH Undisturbed: **b** LH Remolded; **c** BM Undisturbed; **d** BM Remolded

generally agree very well with those obtained from the experiment, indicating that the selected soil model and input parameters are appropriate. However, there are still some deviations between the numerical and experimental results. For example, the simulated settlement curve of each loading step increases quickly in a short period of time before it becomes almost stable, whereas the experimental curve demonstrates a more gently increasing trend with time until the end of the loading step. This deviation is also observed in studies comparing consolidation settlements obtained from the numerical analysis (FEM) and monitoring, especially for unit cell study (Indraratna et al. 2005; Nguyen et al. 2022). This can be explained by the following reasons. The constitutive soil models such as the Soft Soil model adopted in the current study usually account for primary consolidation only, whereas structural effect, which is often prominent in natural soils, is ignored. This leads to the faster development of settlement in the initial stage followed by almost constant level later as induced by the rapid dissipation of excess pore water pressure in the radial unit cell.

However, in the experiment, the settlement of soil was contributed by both primary and secondary consolidation, which resulted in more gradual develop of settlement, especially in later stage. It is noteworthy that the coefficient of horizontal permeability k_x, the key influencing parameter on radial consolidation, was obtained from RC tests, whereas other parameters such as C_c and C_r were obtained from vertical consolidation tests according to standard guidelines.

It is also worth noting that the permeability change index C_{k} [$= \Delta e/\log(k_2/k_1)$] also affects the settlement of both numerical analysis and experiment. The RC test results from different drain diameters indicate that smaller drain diameter resulted in larger C_{k} value (i.e., $C_{\mathrm{k,CD12}} > C_{\mathrm{k,CD20}} > C_{\mathrm{k,CD28}}$). By considering the same drain diameter, the undisturbed soil specimen resulted in larger C_{k} compared with that from the remolded soil specimen. These features of C_{k} were taken into account while implementing the numerical analysis.

The good agreement between numerical and experimental results indicates that the soil parameters determined through a series of laboratory studies in this study can be used to model soil consolidation induced by PVDs. The permeability in horizontal direction can be calculated from the permeability in vertical direction by using a factor of 2.0 to 3.0. The permeability change index C_{k}, which is important to represent nonlinear consolidation behaviour of soil, was found reasonably at 0.2 to 0.35 for the soft soil in Red River Delta.

5 Limitations and Suggestions for Future Studies

Although this study has significantly improved our understanding of the influence that varying diameter of central drain on the value of c_r in radial consolidation test for different clayey soils in Red River Delta, several limitations remain. Firstly, the influence of smear zone was not considered in both experimental and numerical studies. Secondly, there was a lack of quantitative measurement and observations of soil structure, though its influence on soil behaviour was evident when comparing undisturbed and remolded samples. Finally, the numerical models need significant improvement including input parameters and selected soil models. These limitations suggest the need for further studies to improve our understanding of the governing factors on the coefficient of radial consolidation, thereby promoting the confidence in selection of design parameters as well as achieving cost-effective solutions.

6 Conclusions

This study investigated consolidation behaviours of clayey soil at three different locations, i.e., Bao Minh, Lai Cach and Lach Huyen in Red River Delta, where the demand for ground improvement has been increasing rapidly in the past decade. Undisturbed soil sampling and CPTu tests were carried out at the 3 locations. Undisturbed soil samples collected from these sites were subjected to a series of radial and vertical consolidation tests in which the effects of soil remolding and the drain diameter were considered. Salient findings from the study can be highlighted as follows:

- Lach Huyen soil was influenced by complex geological activities, both fluvial and oceanic processes, and recent excessive reclamations (dredging), it thus has younger geotechnical profile compared to those in Bao Minh and Lai Cach sites which are predominantly governed by fluvial processes. The clayey soil in Lach Huyen has smaller shear strength and larger compressibility, resulting in larger settlement under the same pressure, whereas the recent construction of sand layer has not affected significantly the level of OCR. In all locations, the OCR varied from 1.0 to 1.8 for clayey soils (5-15 m). On the other hand, Bao Minh soil has largest coefficients of permeability and coefficients of consolidation, which are about 4–5 times larger than those in two other sites.
- Three drain diameters, i.e., $D_{\mathrm{w}} = 12$, 20, and 28 mm (corresponding to drain spacing ratio $n = D_{\mathrm{e}}/D_{\mathrm{w}}$ of 5.17, 3.10, and 2.21) were investigated in the study. The test results indicate that the drain diameter (i.e., the horizontal drainage length of soil specimen) significantly impacted the calculated c_r. In general, the smaller drain diameter (i.e., larger n) resulted in larger value of c_{r}. The c_{r} value was found to increase significantly when n increased from 2.21 to 3.10, however when n continued to increase from 3.1 to 5.17, the influence of drain diameter became

less significant. This behavior can mainly be attributed to characteristics of natural soil. The determination of c_r from the radial consolidation tests must be considered with reference to the diameter of central drain. New correlations for the coefficient of radial consolidation calculated by different drain diameters were proposed that gave valuable implications to practical designs.

- Soil remolding can make the permeability and coefficient of consolidation of clayey soils change significantly by a factor of from 2 to 10, depending on locations. For Lai Cach and Lach Huyen soils, c_r was found to decrease by a factor of 2–3, but it decreased by a factor of 5–10 for Bao Minh soil.
- The numerical simulation of RC test using Soft Soil model was carried out on undisturbed and remolded soils adopting the set of input parameters obtained from the experimental study. The cumulative time – settlement curves obtained from the numerical analysis were found to agree well with the experimental curves. Besides consolidation parameters, the permeability change index C_k, which was found reasonable in a range of 0.20–0.35 for clayey soils in the Red River Delta, can affect the numerical results of radial consolidation significantly.

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Data Availability The data used in the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

ASTM D1452 (2009) Standard practice for soil exporation and sampling by auger borings. American Society for Testing and Materials, West Conshohocken

ASTM D1587 (2009) Standard practice for thin-walled tube sampling of soils for geotechnical purposes. American Society for Testing and Materials, West Conshohocken

ASTM D2435 (2011) Standard test methods for one-dimentional consolidation properties of soils using incremental loading. American Society for Testing and Materials, West Conshohocken

Barron RA (1948) The influence of drain wells on the consolidation of fine-grained soils. Trans ASCE 113(2348):718–754

Bergado DT, Balasubramaniam AS, Fannin RJ, Holtz RD (2002) Prefabricated vertical drains (PVDs) in soft Bangkok clay: a case study of the new Bangkok international airport project. Can Geotech J 39(2):304–315. https://doi.org/10.1139/t01-100

Berry PL, Wilkinson WB (1969) The radial consolidation of clay soils. Géotechnique 19(2):253–284. https://doi.org/10.1680/geot.1969.19.2.253

Chung SG, Park TR, Hwang DY, Kweon HJ (2018) Full-match method to determine the coefficient of radial consolidation. Geotech Test J 42(5):1298–1313. https://doi.org/10.1520/gtj20170459

Guglielmi S, Cotecchia F, Cafaro F, Gens A (2024) Analysis of the micro to macro response of clays to compression. Géotechnique 74(2):134–154. https://doi.org/10.1680/jgeot.21.00233

Hansbo S (1979) Consolidation of clay by band shaped prefabricated drains. Ground Eng 12(5):16–25. https://doi.org/10.1016/0148-9062(80)90141-2

Indraratna B, Redana IW (1998) Development of the smear zone around vertical band drains. Ground Improve 2(4):165–178. https://doi.org/10.1680/gi.1998.020403

Indraratna B, Rujikiatkamjorn C, Sathananthan I (2005) Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading. Can Geotech J 42(4):994–1014. https://doi.org/10.1139/t05-029

Indraratna B, Nguyen TT, Carter J, Rujikiatkamjorn C (2016) Influence of biodegradable natural fibre drains on the

radial consolidation of soft soil. Comput Geotech 78:171–180. https://doi.org/10.1016/j.compgeo.2016.05.013
Khin PS (2022) Compressibility characteristics of soft clays in the Red River delta. Vietnam Japan University
Kuganeswaran N, Rahim A, Ali N (2021) Consolidation in soft soil—case study on prefabricated vertical drains (PVDs). Open Civ Eng J 15:310–319. https://doi.org/10.2174/1874149502115010310
Lam LG, Bergado DT, Hino T (2015) PVD improvement of soft Bangkok clay with and without vacuum preloading using analytical and numerical analyses. Geotext Geomembr 43(6):547–557. https://doi.org/10.1016/j.geotexmem.2015.07.013
Liu MD, Carter JP (2002) A structured Cam Clay model. Can Geotech J 39(6):1313–1332. https://doi.org/10.1139/t02-069
Nguyen TT, Indraratna B (2023) Natural fibre for geotechnical applications: concepts achievements and challenges. Sustainability 15(11):8603. https://doi.org/10.3390/su15118603
Nguyen TD, Khin PS (2023) Compressibility characteristics of clays in the Red River delta. J Sci Technol Civ Eng JSCTE 17(1):41–57. https://doi.org/10.31814/stce.nuce2023-17(1)-04
Nguyen B-P, Nguyen TT, Nguyen THY, Tran T-D (2022) Performance of composite PVD-SC column foundation under embankment through plane-strain numerical analysis. Int J Geomech 22(9):04022155. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002494
Phuc TT, Giao PH (2020) Geotechnical properties of Hai Phong and Ninh Binh clays in the Red River Delta. In: Duc Long P, Dung NT, (eds.), Proceedings of the Geotechnics for Sustainable Infrastructure Development. Springer Singapore, Singapore. pp. 751–758
Robertson PK (2009) Interpretation of cone penetration tests—a unified approach. Can Geotech J 46(11):1337–1355. https://doi.org/10.1139/t09-065
Robinson RG (1997) Determination of radial coefficient of consolidation by the inflection point method. Géotechnique 47(5):1079–1081. https://doi.org/10.1680/geot.1997.47.5.1079
Robinson RG (2008) Analysis of radial consolidation test data using a log-log method. Geotech Test J 32(2):119–125. https://doi.org/10.1520/GTJ101034
Robinson R, Allam M (1998) Analysis of consolidation data by a non-graphical matching method. Geotech Test J 21(2):140–143. https://doi.org/10.1520/gtj10752j
Seah T, Tangthansup B, Wongsatian P (2004) Horizontal coefficient of consolidation of soft Bangkok clay. Geotech Test J 27(5):430–440. https://doi.org/10.1520/gtj11777
Shields DH, Rowe PW (1965) A radial drainage oedometer for laminated clays. J Soil Mech Found Div 19(4):421–431
Silva IN, Indraratna B, Nguyen TT, Rujikiatkamjorn C (2024) The influence of soil fabric on the monotonic and cyclic shear behaviour of consolidated and compacted specimens. Can Geotech J. https://doi.org/10.1139/cgj-2023-0141
Sridhar G, Robinson R (2011) Determination of radial coefficient of consolidation using log *t* method. Int J Geotech Eng 5(4):373–381. https://doi.org/10.3328/IJGE.2011.05.04.373-381
Sridhar G, Robinson RG, Karpurapu R (2018) Horizontal coefficient of consolidation from inward- and outward-flow tests. Proc Inst Civ Eng Ground Improve 171(3):159–166. https://doi.org/10.1680/jgrim.17.00056
Tanabe S, Saito Y, Lan Vu Q, Hanebuth TJJ, Lan Ngo Q, Kitamura A (2006) Holocene evolution of the Song Hong (Red River) delta system, northern Vietnam. Sedimen Geol 187(1):29–61. https://doi.org/10.1016/j.sedgeo.2005.12.004
Vinod JS, Sridharan A, Indraratna B (2010) Determination of coefficient of radial consolidation using steepest tangent fitting method. Geotech Geol Eng 28(4):533–536. https://doi.org/10.1007/s10706-010-9330-8
Waheed MQ, Asmael NM (2024) Using soft soil models in geotechnical engineering: a review paper. E3S Web of Conf 531:04018
Yune C-Y, Chung C-K (2005) Consolidation test at constant rate of strain for radial drainage. Geotech Test J 28(1):71–78. https://doi.org/10.1520/gtj11922
Zhao B, Zhou Y (2022) Influence of drain installation-induced stress on the consolidation of a natural soft foundation. Geotech Geol Eng 40(12):5769–5780. https://doi.org/10.1007/s10706-022-02248-w