Laboratory Studies on the Characteristics of Public Fill used in Reclamation Project in the Deep-sea Area

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doi: https://doi.org/10.21467/proceedings.133.28

ABSTRACT

To reduce solid wastes and recover useful resources, an artificial island in the deep-sea area was built and it was planned to use the sorted public fill as the replacement of sand in the land reclamation. The use of the public fill as the replacement of sand not only reduced the CO_2 emission, but also shortened the construction period. Although the use of public fill gives benefits to environmental sustainability, the public fill is rarely used in Hong Kong for reclamation in the deep-sea artificial island. Furthermore, the short-term and long-term post-construction settlement due to surcharge load is a key issue in the reclamation work, while limited information of the physical and mechanical properties of the public fill could be found in the past engineering projects. In addition, there are many uncertainties and influencing factors in the construction site such as the surcharge load magnitudes, modes of the loading process, and the variability of geotechnical parameters. How these factors influence the mechanical behavior of the public fill is an interesting issue. This paper gives first-hand laboratory test results accompanied by theoretical analysis to address the mentioned issues. After a comprehensive and careful measurement of several basic engineering properties, such as bulk density, particle size distribution, and Atterberg limits, large-scale oedometer tests were systematically conducted to study the compressibility of the public fill. It is found both volume compressibility and consolidation coefficient decrease with an increasing axial effective stress. An interesting finding is that an increasing fines content with a certain range will lead to an increase in the compressibility of the public fill, indicating the fines content may need to be considered in the land reclamation works. In addition, remarkable creep could be observed if the current vertical stress is lower than the preloading pressure. After obtaining design parameters and ensuring allowable settlement through both in-house laboratory tests and in-situ field tests, the project in the technical paper may be a good reference for future land reclamation design and construction cases.

Keywords: Public Fill, Compressibility, Creep

1 Introduction

The project was constructed to substantially reduce the bulk size of mixed waste and to recover useful resources. The project was built on an artificial island in the deep sea. In this project, it was planned to use the sorted public fill as the replacement of sand in the land reclamation. Although the use of public fill gives benefits to construction cost and environmental sustainability development compared to sand, the public fill is rarely used in Hong Kong for reclamation in the deep-sea artificial island. Furthermore, the short-term and long-term post-construction settlement due to surcharge load is a key issue in the reclamation work. Accurate estimation of consolidation settlement is very important during design of reclamation structures. In geotechnical engineering, standard oedometer tests are conducted to investigate compressibility of soils due to applied loading. The tests are performed by adding constraint of zero radial strain and applying axial stress under saturated conditions, in which the excess pore-water pressure dissipates with time, leading to deformation. Terzaghi (1943) was the first one who proposed mathematical theory of one-dimensional consolidation. However, Terzaghi's theory did not consider the creep effect of clayey soils. In reclamation projects in Hong Kong, ground settlements are mainly

Proceedings DOI: 10.21467/proceedings.133; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-957605-1-0

due to creep, water level change, and surcharge. This implies the creep behaviors of clayey soils are very important in HK local practice. Yin and Graham (1996) proposed an elastic visco-plastic (EVP) constitutive model to calculate settlements and excess pore water pressures in clays under multi-stage constant vertical loads. The EVP model was used to study the influence of soil thickness on settlements, pore water pressure dissipation, stress and strain. It was concluded the model was capable to simulate the viscous nature of soils and the predicted results were in good agreement with the test data. The framework gives simple and helpful way to estimate creep behavior in reclamation work (Nash and Ryde, 2001; Feng *et al*., 2017).

This paper gives first-hand laboratory test results accompanied by theoretical analysis to explore the mechanical behavior of the public fill used in the deep-sea area. After a comprehensive and careful measurement of several basic engineering properties, such as bulk density, particle size distribution, and Atterberg limits, large-scale oedometer tests were systematically conducted to study the compressibility of the public fill. It is found both volume compressibility and consolidation coefficient decrease with an increasing axial effective stress. An interesting finding is that an increasing fines content with a certain range will lead to an increase in the compressibility of the public fill, indicating the fines content may need to be considered in the land reclamation works. In addition, remarkable creep could be observed if the current vertical stress is lower than the preloading pressure. After obtaining design parameters and ensuring allowable settlement through both in-house laboratory tests and in-situ field tests, the project in the technical paper may be a good reference for future land reclamation design and construction cases.

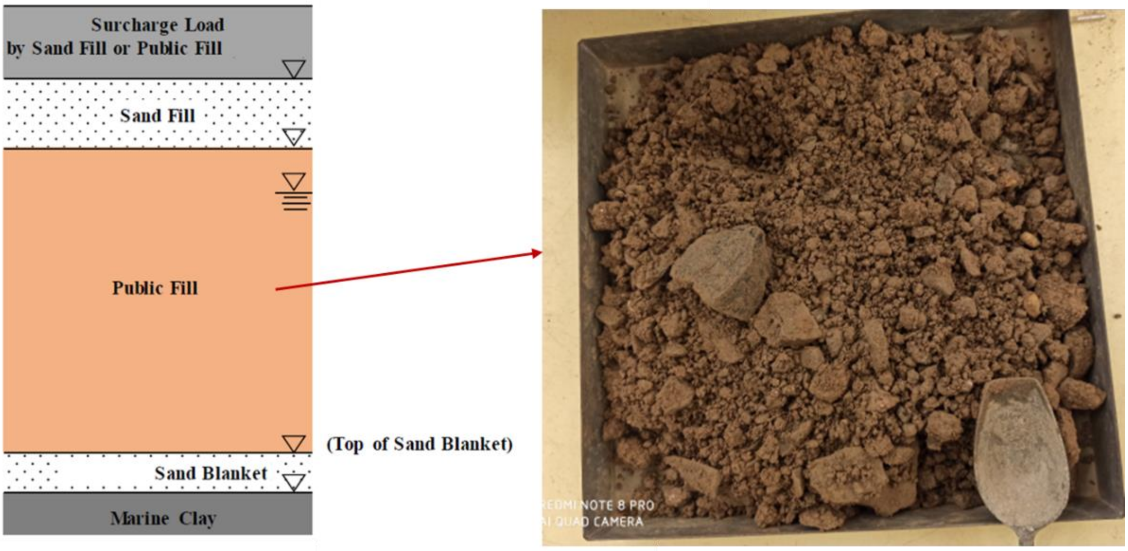

Figure 1: Simplified soil profiles and public fill used in the tests

2 Test Arrangements

2.1 Test for Basic Physical Properties

The tests were conducted in the laboratory in the Hong Kong Polytechnic University and detailed summary of the test procedures and test data analysis was conducted by Liu *et al*. (2020). Before conducting oedometer test, the basic physical properties of the public fill (e.g., particle size distribution, moisture content, relative density, and Atterberg limits) was determined in the soil laboratory. It should be noted the test procedures of maximum dry density test, PSD test, Atterberg limits test were in accordance with GeoSpec. 3 (2017). The minimum dry density test was conducted based on BS 1377-4 (2002). Figure 2 shows the PSD curve of the public fill. Table 1 summarizes the basic properties of the public fill in the test No. LOT-2, LOT-4, LOT5.

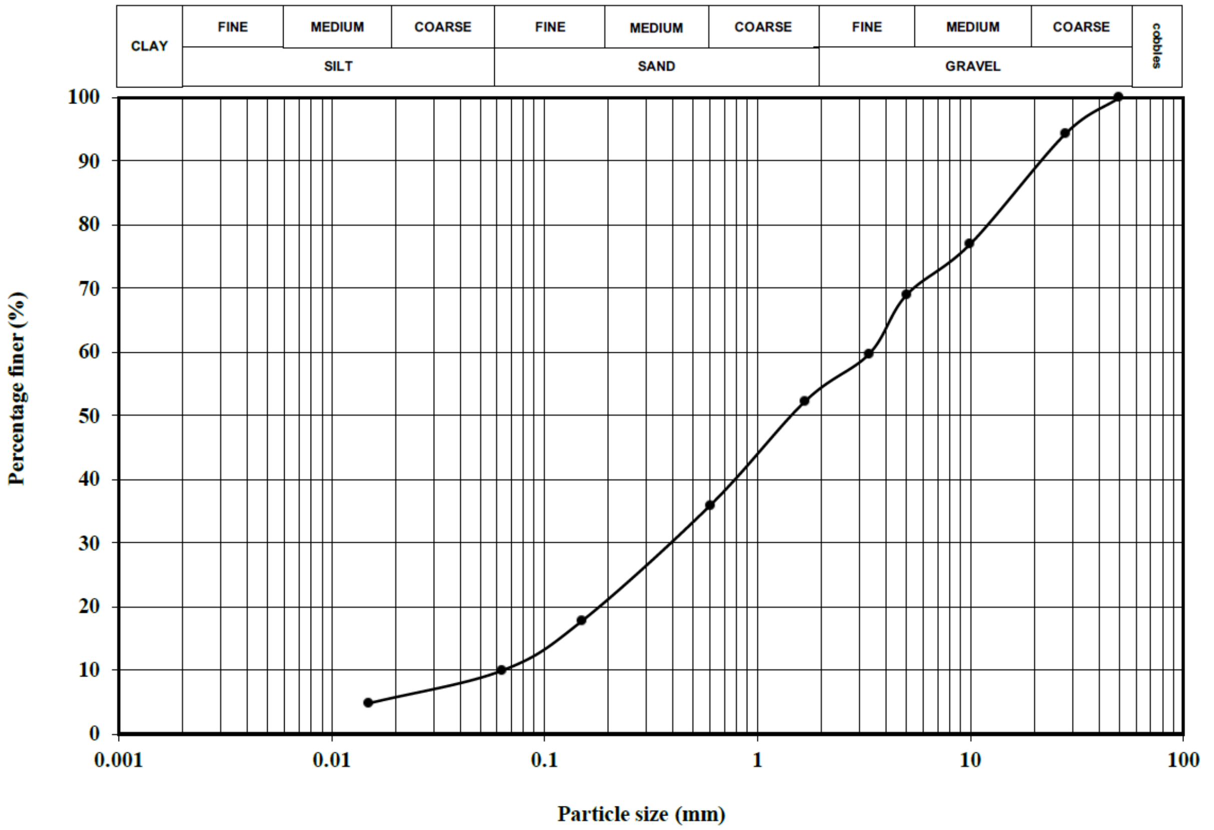

Figure 2: Particle size distribution of test No. LOT-2

Table 1: Summary of PSD, Atterberg limits, optimum water content, and maximum dry density

Test Items	LOT-2	LOT-4/LOT5
Particle Size Distribution:		
D_{60} (mm)	3.35	1.5
D_{10} (mm)	0.063	0.018
C_u (mm)	53.17	83.33
Atterberg Limits:		
Plastic limit (%)	-	28.3
Liquid limit (%)	-	43.2
Plasticity index (%)	-	14.9
Optimum Water Content and Maximum Dry Density:		
Optimum water content (%)	12.3	16.8
Maximum dry density (g/cm^3)	2.256	2.161

2.2 Multi-staged Large-scale Oedometer Test

Figure 3 shows the arrangements of the large-scale oedometer test. Specifically, a steel-made cylinder model with a diameter of 300 mm and a height of 450 mm was used to conduct the large-scale oedometer tests. A pore water pressure transducer was placed in the large-scale oedometer test to monitor the changes of pore water pressure. The axial effective stress, vertical displacement, pore water pressure, and time were measured during the test process. There are three test schemes LOT-2, LOT-4, and LOT-5, which were conducted under various initial void ratios, fines content, and loading sequence. For test scheme LOT-2, the moisture content and relative density at 25kPa effective stress are 34.2% and 52.8%. The void ratio after sample preparation is 0.742 and the void ratio after test is about 0.534. The detailed procedures of the multi-stages oedometer test is summarized as follows:

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0

Series: AIJR Proceedings
ISSN: 2582-3922

(a) (b)

Figure 3. Multi-staged large-scale oedometer test: (a) 25kPa stage; (b) 200 kPa stage

a) Calibrate the displacement and pore water transducers.
b) Set up the cropped permeable geotextile membranes and filter paper at the bottom. Weigh and place the public fill in the cylinder model. Place filter paper, permeable geotextile membrane, and punched steel plate on the soil surface.
c) Apply an initial loading.
d) Weigh and place the public fill by controlling a constant height. Place a pore water pressure transducer in the middle of the second layer.
e) Conduct multi-stages oedometer tests with various loading sequence. For example, LOT-2 test was conducted by increasing axial stress from 25kPa to 400kPa. An unloading stage was performed by reducing axial stress from 400kPa to 200kPa. A one-week creep test was conducted by keeping axial effective stress of 200kPa for one week. Measure the settlement and pore water pressure at all test stages.
f) Measure the moisture content after completion of test.

3 Results and Discussion

In this part, detailed discussion of the test results will be conducted, particular emphasis is given to explore the compressibility and time-dependent behavior of the public fill.

3.1 Compressibility Parameters of the Public Fill

The public fill is the inert material arising from construction and demolition activities which was used in the reclamation and building of artificial island in deep sea, the compressibility of the material is an important factor in the deformation prediction. In this study, some compressibility parameters are introduced and calibrated based on test results, which may improve and complete the test database of the soils in this project. To evaluate the compressibility of the public fill, the variation of the axial strain with the axial effective stress is plotted in Figure 4. During data analysis, the compression parameter (λ/V), which is defined as the slope of the consolidation path in the ε_z and $\ln(\sigma_z)$ plot, is proposed to measure the engineering properties of the public fill:

$$\frac{\lambda}{V} = \frac{\Delta \varepsilon_z}{\Delta \ln \sigma_z} \qquad \textbf{(1)}$$

where $\Delta\varepsilon_z$ = change of the axial strain, $\Delta \ln \sigma_z$ = change of the axial stress, $V = 1 + e_0$ is the initial specific volume, e_0 is the initial void ratio. The compression ratio (CR) and the recompression ratio (RR) are introduced to evaluate soil behaviors under normal consolidated and over-consolidated conditions.

$$CR = \frac{C_c}{V} = 2.3\frac{\lambda}{V} \quad \textbf{(2)}$$

$$RR = \frac{C_r}{V} = 2.3\frac{\kappa}{V} \quad \textbf{(3)}$$

where κ = the slope of the unloading or reloading path in the ε_z and $\ln(\sigma_z)$ plot of soils under over-consolidated conditions. The volume compressibility (m_v) is defined as follows:

$$m_v = \frac{\Delta\varepsilon}{\Delta\sigma} \quad \textbf{(4)}$$

where $\Delta\varepsilon$ = the change of the strain, $\Delta\sigma$ = the change of effective stress. In this study, the coefficients of consolidation are evaluated using Casagrande Logarithm of Time Method (CA) and Taylor Square Root of Time Method (TA) (Olek, 2019). Specifically, the coefficient using CA method is defined as $C_v = 0.197H^2/t_{50}$, and TA method gives $C_v = 0.848H^2/t_{90}$, where Cv is coefficient of consolidation, t_{50} is time period for 50% consolidation, t_{90} is time period for 90% consolidation.

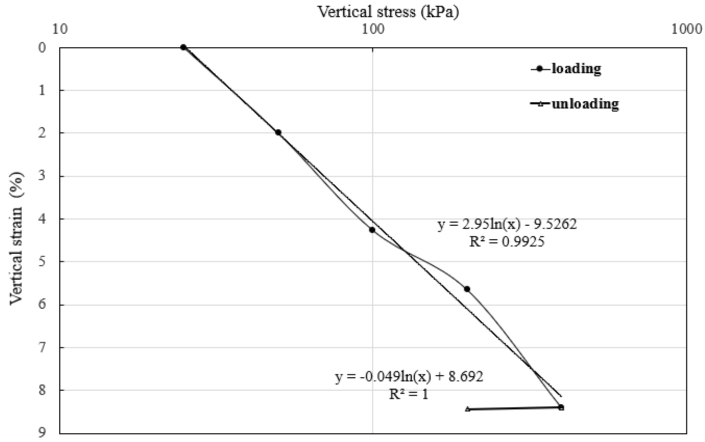

Figure 4: The variation of axial strain with axial effective stress in No. LOT-2 test

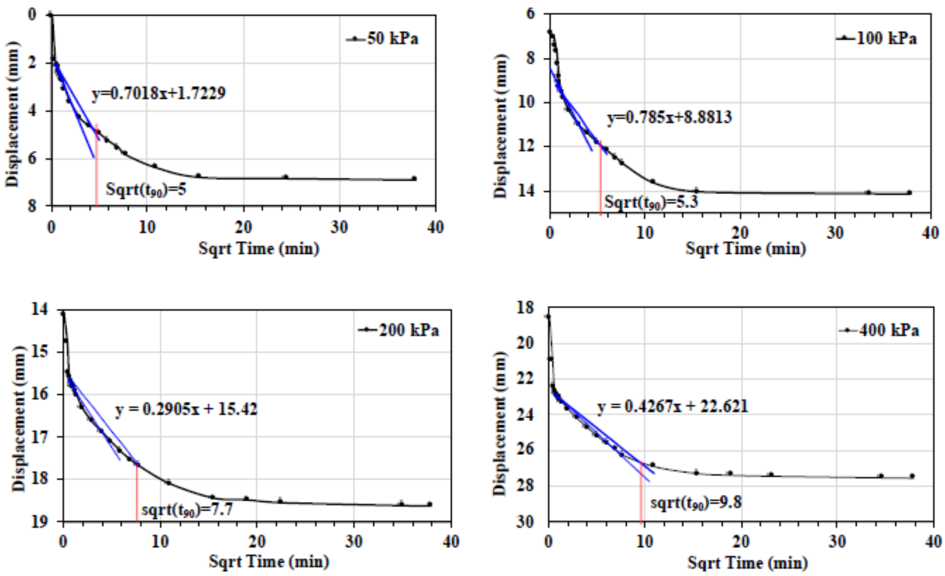

Figure 5: The coefficients of consolidation evaluated using Taylor Square Root of Time Method (TA) in No. LOT-2 test

Figure 4 shows the relationship between axial/vertical strain and axial/vertical effective stress of the public fill in No. LOT-2 test. There are two test stages, namely, loading and unloading. The compression parameter, compression ratio, recompression ratio, volume compressibility could be directly or indirectly obtained from the data points after conducting data analysis. Figure 5 gives detailed procedure of evaluating consolidation coefficients of the soil sample subjected to various axial effective stresses. Table 2 gives a comprehensive summary of compressibility parameters of LOT-2, LOT-4, LOT-5 tests with various axial effective stress and void ratio. It can be found the compression parameters (λ/V) of LOT-2, LOT-4, LOT-5 are 0.0295, 0.0433, and 0.0420, respectively. The compression ratios (CR) of these samples are 0.07, 0.10, 0.10. The recompression ratios (RR) are 0.00113, 0.00873, 0.00562. It can be observed that the volume compressibility (m_v), the coefficients of consolidation based on CA and TA methods are sensitive to the axial effective stress, and those mechanical coefficients decrease with an increasing axial effective stress. It should be noted different compressibility parameters of the public fill of LOT-2, LOT-4, LOT-5 may be due to different particle size distribution, particle minerology, fines content of test materials.

Table 2. Summary of compressibility parameters of the test materials

Test No.	Axial effective stress (kPa)	Void ratio (-)	λ/V (-)	κ/V (-)	CR (-)	RR (-)	m_v (kPa^{-1})	C_v based on CA (m^2/year)	C_v based on TA (m^2/year)
LOT-2	50	0.644	0.0295	0.00049	0.07	0.00113	0.00080	304.01	418.76
	100	0.606					0.00045	262.53	362.08
	200	0.583					0.00014	139.13	161.62
	400	0.536					0.00014	138.88	99.60
LOT-4	50	0.793	0.0433	0.00379	0.10	0.00873	0.00176	110.97	83.07
	100	0.751					0.00058	48.30	47.14
	200	0.705					0.00023	46.07	57.50
	400	0.650					0.00014	43.58	54.39
LOT-5	50	0.838	0.0420	0.00244	0.10	0.00562	0.00135	79.06	82.57
	100	0.791					0.00058	60.91	40.01
	200	0.741					0.00025	59.07	38.45
	400	0.683					0.00016	58.11	38.39

The fines content can influence the mechanical behavior of soils (Yang and Wei, 2012). To validate the effect of fines content on the compressibility of the public fill, the fines contents of three samples of LOT-2, LOT-4, LOT-5 were quantified using the results from particle size distribution (PSD) tests, and the fines contents of LOT-2, LOT-4, and LOT-5 are 11%, 26%, and 26%. Figure 6 shows the influence of the fines content on the compressibility (m_v) of the public fill. Clearly, it can be observed that an increase of the fines content from 11% to 26% could lead to an increase of m_v of materials subjected to various axial effective stress, which means an increasing fines content with a certain range will lead to an increase in the compressibility of the public fill and the fines content may need to be considered during design and construction of the land reclamation works.

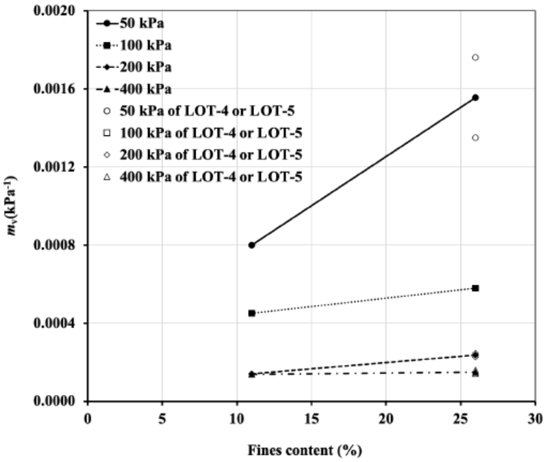

Figure 6: The effect of fines content on m_v

3.2 Creep Behaviour

The time-dependent mechanical behavior of soils is very important to estimate the long-term settlement of ground in the land reclamation works. Feng *et al.* (2017) studied the long-term non-linear creep and swelling behavior of marine deposits by doing oedometer tests. Detailed interpretation and discussion of creep/swelling behaviors and the mechanism of granular particles was made, contributing to in-depth understanding of long-term non-linear creep and swelling behavior of HK Marine Deposit. In this study, the creep behavior of the public fill will be summarized using the test results from Liu *et al.* (2020).

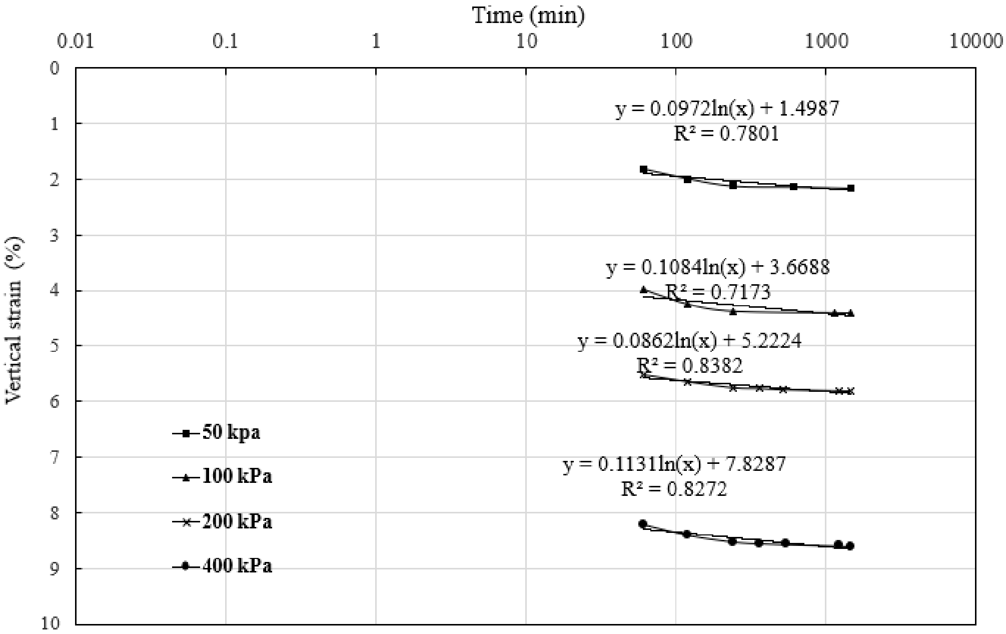

Figure 7: The relationship between axial/vertical strain with time of LOT-2 samples in the oedometer test

Figure 7 shows the relationship between axial/vertical strain with time of LOT-2 samples in the oedometer test. The creep parameter (ψ/V) in defined as follows:

$$\varepsilon_z = \varepsilon_{z0} + \frac{\psi}{V}\ln\left(\frac{t_0^c + t_e^c}{t_0^c}\right) \quad \textbf{(5)}$$

where t_e^c = creep equivalent time proposed by Yin and Graham (1994); t_0^c = time parameter corresponding to the beginning of creep time; ε_{z0} = strain when $t = t_0^c$. After knowing the creep parameter (ψ/V), the logarithmic creep compression rate (α) is defined as follows:

$$\alpha = 2.3\frac{\psi}{V} \quad \textbf{(6)}$$

Table 3 summarizes the creep parameter (ψ/V) and creep compression rate (α). It can be found these creep parameters are sensitive to the axial stress level, loading type, and material characteristics such as fines content and particle size distribution (Feng *et al.*, 2017). Specifically, the loading history, which covers loading, unloading, and reloading process during oedometer test, has significant influence on the creep behavior of sandy soils. It can be found creep parameters (ψ/V) of LOT-4 in the reloading process are smaller compared to creep behavior in the loading process. This means creep behavior is minor if the public fill was subjected to large preloading pressure and the preloading process with reasonable axial stress level should be carefully considered during design and construction of embankment works. It should be noted large preloading pressure is the larger axial effective stress applied at loading stage in the lab test, and it is an observation from the lab test results of LOT-4. When 400kPa axial effective stress is applied at the loading stage, the creep parameter and the logarithmic creep compression rate

Proceedings DOI: 10.21467/proceedings.133
ISBN: 978-81-957605-1-0
Series: AIJR Proceedings
ISSN: 2582-3922

for axial effective stress 50kPa, 100kPa and 200kPa are very small at reloading stage compared with the same axial effective stresses at loading stage. The reduction of the creep behavior if the public fill was subjected to preloading history may be due to loading-history induced particle rearrangement or particle crushing (Liu *et al*., 2020), and more detailed studies such as imaged-based micro-scale analysis or DEM analysis may be needed to further explore the mechanism of loading-history dependent creep behavior. As for the effect of axial stress on the creep behavior during loading stage, it is found that the creep parameter (ψ/V) decreases (despite some deviation) with an increasing axial effective stress. In summary, the test results show that the creep behavior of the public fill is significantly influenced by the preloading history.

Table 3: Creep parameters of the public fills

Test No.	Axial effective stress (kPa)	Loading type	ψ / V (-)	α (%)
LOT-2	50	Loading	0.00097	0.224
	100	Loading	0.00108	0.249
	200	Loading	0.00086	0.198
	400	Loading	0.00113	0.260
LOT-4	50	Loading	0.00400	0.920
	100	Loading	0.00203	0.468
	200	Loading	0.00216	0.497
	400	Loading	0.00196	0.452
	50	Reloading	0.00001	0.001
	100	Reloading	0.00008	0.019
	200	Reloading	0.00012	0.028
LOT-5	50	Loading	0.00299	0.687
	100	Loading	0.00185	0.426
	200	Loading	0.00243	0.559
	400	Loading	0.00096	0.221
	50	Reloading	0.000004	0.001
	100	Reloading	0.000033	0.008
	200	Reloading	0.00005	0.012

It should be noted this technical paper summarizes the compressibility and creep behavior of the public fill in the land reclamation work in the deep sea using in-house laboratory test data. The large scale oedometer tests were conducted using distilled water during the laboratory investigation. Secondly, there are many uncertainties in the construction site such as relative densities, fines content, surcharge load magnitudes and loading history, depth of the public fill, fabric anisotropy, making it challenging to represent and predict short-term and long-term settlement using analytical methods, constitutive models, and FEM software. This means in practice, the ground profiles, material behaviors, performance of constitutive models, model input parameters should be carefully studied and interpreted based on empiricism. In addition, there are many construction activities in the construction site such as excavation and lateral support, bored pile and steel H pile installation, machine foundation design and construction. More detailed numerical and laboratory studies on the drained and undrained shear strength, soil-structure interaction, dynamic properties, liquefaction resistance may need to be further explored in the future.

4 Conclusions

This paper gives first-hand laboratory test results accompanied by theoretical analysis to address the compressibility and the creep of the public fill used in a reclamation work of an artificial island. After a comprehensive and careful measurement of several basic engineering properties, such as bulk density, particle size distribution, and Atterberg limits, large-scale oedometer tests were systematically conducted with different confining pressures and fines contents to study the compressibility of the public fill. It can be found that:

(1) Both volume compressibility and consolidation coefficient decrease with an increasing axial effective stress.

(2) An increasing fines content with a certain range will lead to an increase in the compressibility of the public fill, indicating the fines content may need to be considered in the land reclamation works.

(3) Remarkable creep of the public fill could be observed if the current vertical stress is lower than the preloading pressure.

5. Declarations

5.1 Acknowledgements

The authors would like to thank Prof. Jianhua Yin, Dr. Kai Liu, and Dr. Weiqiang Feng for sharing test data. The authors would like to express gratitude to colleagues in the China Harbour Engineering Corporation for support during paper preparation. The authors would like to thank the Geotechnical Division Committee of the HKIE for giving this opportunity.

5.2 Publisher's Note

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