Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-638

Sustainable land reclamation using locally dredged sediment improved by horizontal and vertical drains – a pilot test in Hong Kong

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ABSTRACT: To address the current challenge of land reclamation, particularly the issue of short supply of fill materials, this paper introduces a sustainable land reclamation approach, in which locally dredged sediments are used as fill materials. A two-step ground improvement method, namely using horizontal drains for preliminary treatment and vertical drain for subsequent treatment combined with vacuum and/or surcharge preloading, is proposed to treat dredged sediments and control the post-construction settlement. The efficiency of the proposed method has been demonstrated by experiments in the laboratory condition. A pilot test has been designed and successfully conducted at Tung Chung New Town Extension site in Hong Kong to study the feasibility of the proposed sustainable land reclamation approach. In this pilot test, Hong Kong marine deposits (HKMD) slurry was used as fill materials and treated by prefabricated horizontal drains (PHDs) with vacuum preloading under a "membrane-free" condition. During the pilot test period, settlement, pore pressure, effective stress, vacuum pressure, water content, and undrained shear strength were recorded. After a four-month treatment, the average water content of HKMD dropped to one-third of the initial water content and HKMD gained sufficient undrained shear strength, indicating the feasibility of the proposed method. Furthermore, a simplified method of practical value has been developed and employed to simulate the settlement of the HKMD in the pilot test.

KEYWORDS: Reclamation, dredged sediment, horizontal drain, vertical drain, pilot test.

1 INTRODUCTION

Land reclamation has been a key source of land supply for many coastal cities. Hong Kong, for instance, has reclaimed 7,820 hectares of land (equivalent to 7% of its total land area) since 1841. To support the further development of this densely populated coastal city, strategic reclamation projects have been planned. However, a key challenge lies in the short supply of conventional fill materials, such as sand. To address this challenge, public fills, including inert construction wastes, have been proposed as an alternative for reclamation. Meanwhile, maintenance dredging and port works in Hong Kong produce around 1.5 million m^3 of dredged marine sediments annually. Those locally dredged sediments that were considered as waste could potentially serve as fill materials for reclamation. Considering the high initial water content and high compressibility of dredged sediments, rapid and effective ground improvement techniques are of great importance to reduce the water content and increase the strength of the dredged sediments. With this regard, Yin et al. (2022a and 2024) developed a new land reclamation approach using dredged sediments together with a combined ground improvement method. Figure. 1 illustrates the proposed land reclamation approach. In this proposed approach, the first step is to construct seawalls and to conduct related ground improvement for the construction of seawalls. The second step is to blow-fill locally dredged sediments into the areas enclosed by the seawalls and to perform the combined ground improvement method using horizontal and vertical drains.

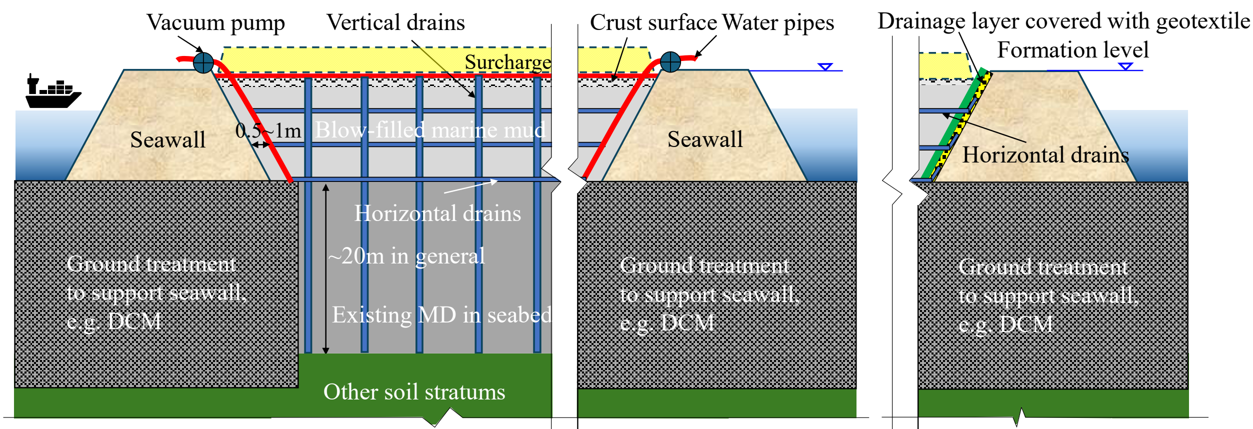

Figure 1. Illustration of the sustainable land reclamation approach

The combined ground improvement method is a two-stage method: (i) preliminary treatment, employing prefabricated horizontal drains (PHDs) with vacuum and/or surcharge preloading, followed by (ii) secondary treatment, using PHDs and prefabricated vertical drains (PVDs) for further treatment with vacuum and/or surcharge preloading. Some promising results on using PHDs and PVDs to quickly consolidate soft soils with high water content in laboratory conditions can be found in Pan et al. (2025). In order to ensure that dredged sediments can be turned into competent fill materials using the proposed ground improvement method, a pilot test was conducted to investigate the effectiveness of the preliminary treatment of dredged sediments using PHDs with vacuum preloading.

2 PILOT TEST

2.1 *Design and implementation*

The pilot test was conducted in a testing pit located at a newly reclaimed site, namely Tung Chung New Town Extension Site, in Hong Kong (Figure 2(a)). The testing pit has a base size of 12 m × 8 m and a depth of 3.5 m with the level of the bottom surface at +3.0 mPD (Principal Datum). The slope along the long side is 1:1.5, and the slope along the short side, for which three levels of berms were constructed, is 1:1.

Hong Kong marine deposits (HKMD), dredged from the seabed south of Lantau Island, were used as the fill for the pilot test. The dredged HKMD used in the pilot test is termed as upper soft clay and classified as the Hang Hau Formation. Hang Hau formation is a generally uniform deposits of very soft to soft greenish grey silty clays which was the most widely developed of the superficial marine deposits involved in dredging works. For instance, it was most entirely removed by dredging operations for the construction of the Hong Kong International airport (Plant et al. 1998). Table 1 lists the basic properties of dredged HKMD. Prefabricated band drains (100 mm in width, 5 mm in thickness, 2,000 N in tensile strength), Style No. VD-808 (T5) manufactured by DAEHAN *i.m.*, were used as PHDs for the pilot test. The prefabricated band drain consists of a polypropylene core and a nonwoven filter layer. Four vacuum pumps (7.5 kW for each) were employed and located at four corners, namely, the east-northern (EN), west-northern (WN), west-southern (WS), and east-southern (ES) of the testing pit.

Table 1. Basic properties of HKMD fill used in the pilot test

Property	Value
Liquid limit	48%
Plasticity index	19%
Clay content	12%
Initial water content	150%

2.2 *Implementation*

Filling process of HKMD fill was divided into four layers, with PHDs installed on the bottom of the pit as well as the top of 1st, 2nd, and 3rd HKMD layers (four layers of PHDs in total). The settlement of each HKMD layer was measured by settlement plates. Vibrating wire piezometers (VWPs) were installed at different locations to monitor the pore pressure of HKMD fill, as shown in Figure 2(b) and (c). Multisamplers and vane testers were employed to sample soil for water content measurement and measure the undrained shear strength at different locations, as shown in Figure 2(b). Table 2 summarizes the implementation details of the pilot test.

The treatment duration of vacuum preloading was around four months (March to July).

3 TEST RESULTS

3.1 *Settlement and pore pressure*

Based on the measured surface settlement, the ultimate settlement of 0.238 m can be estimated using Asaoka's method, as shown in Figure 3(a). The final measured surface settlement was 0.230. Therefore, the degree of consolidation (DOC) of the treated HKMD fill can be estimated as 0.230/0.238 = 96.6%.

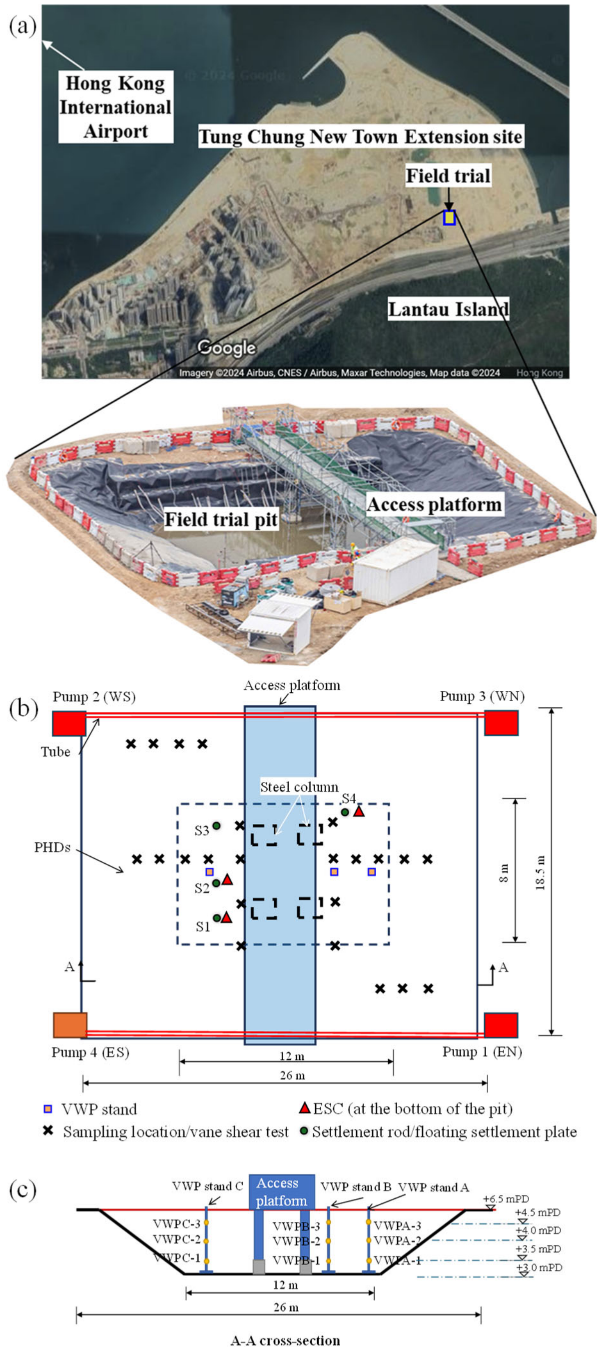

Figure 2. (a) Location; (b) schematic drawing (top view); and (c) A-A cross-section view of the testing pit

Figure 3(b) presents the profiles of average pore pressure monitored at different times. The maximum pore pressure was recorded on 02/22/22 (mm/dd/yy), due to the filling process and the overburden. A significant decrease in pore pressure measured at +3.5 mPD on 04/02/22 agreed with the fact that vacuum pressure was only applied to the first two layers of PHDs (initial levels of +3 mPD and +3.5 mPD). Starting from 04/19/22, vacuum pressure was applied to all four layers of PHDs. Notable decreases in pore pressure can be observed at all levels on 05/05/22. The reason why the pore pressure at +4.0 mPD exceeded those at +3.5 and +4.5 mPD can be explained by the fact that the VMP at +4.0 mPD was located between the levels of the 3rd and 4th layers of PHDs, while those at +3.5 and +4.5 mPD were located closer to the PHDs. Further decreases in pore pressure can be observed at +4.0 and +4.5 mPD on 06/30/22. After that, the reading of the VMPs was affected by heavy rainfall and therefore not presented here. Based on the pore pressure profile, the estimated average degree of consolidation was around 77.9%. The average degree of consolidation estimated by pore pressure is found to be lower than that estimated by settlement. This can be attributed to the susceptibility of pore pressure data to heavy rainfall or the nonlinear stress–strain behavior of soft soil

Table 2. Record of activities

Item		Date (mm/dd/yy)
Filling process	1st layer	12/22/21-12/28/21
	2nd layer	01/19/22-02/07/22
	3rd layer	02/08/22-02/14/22
	4th layer	02/17/22-02/22/22; 03/29/22-04/02/22
Vacuum application	Bottom two layers of PHDs only	03/09/22-03/18/22
	All four layers of PHDs	04/19/22-07/23/22
Pore pressure monitoring		03/06/22-07/23/22
Recording of settlement/level	Surface	12/22/21-07/25/22
	At the top of the 1st layer of HKMD	01/29/22-07/25/22
	At the top of the 2nd layer of HKMD	02/10/22-07/25/22
	At the top of the 3rd layer of HKMD	02/16/22-07/25/22
Sampling for water content measurement		02/26/22, 03/26/22, 05/18/22, 06/30,22, 07/15/22, 07/25/22
Undrained shear strength measurement		02/25/22, 04/11/22, 04/24/22, 04/26/22, 05/05/22, 05/18/22, 06/02/22, 06/28/22, 07/25/22

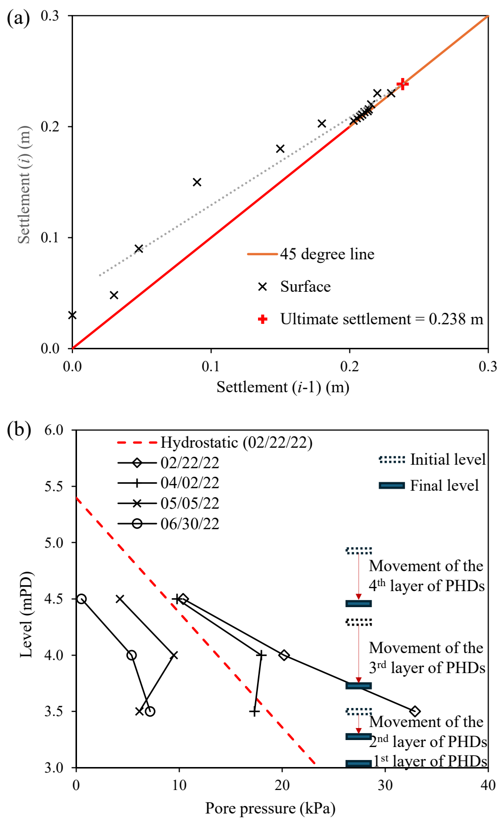

Figure 3. (a) Asaoka's plot of surface settlement and (b) pore pressure profiles

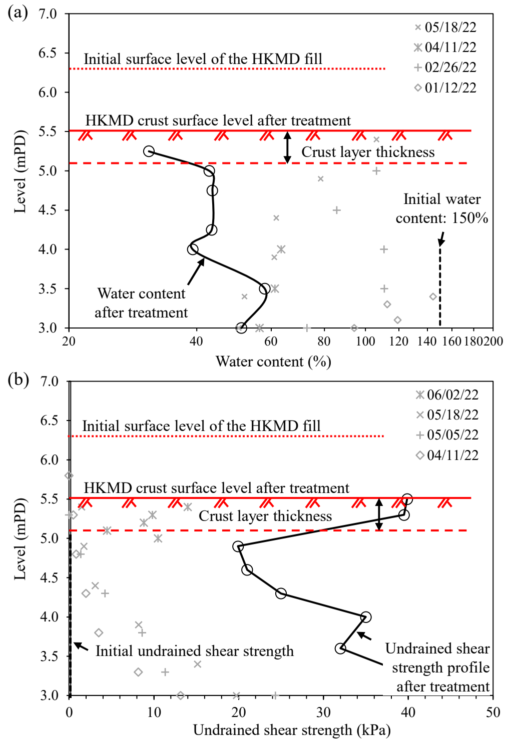

Figure 4. (a) Water content profiles and (b) undrained shear strength profiles

3.2 *Water content and undrained shear strength*

Figure 4(a) shows that the water content of the HKMD fill reduced from 150% to less than 50% after four-month treatment. Owing to the combined effect of the application of the vacuum and drying process, a crust layer was formed on top of the HKMD fill. The water content at the crust surface was 30.8% at the end of the test, which is below the liquid limit (48%) of the HKMD fill.

Figure 4(b) shows the average undrained shear strength profiles of the HKMD fill measured at different times. The locations where the vane shear tests were conducted as indicated in Figure 2(b). Considering the initial water content of the filled HKMD slurry was 150%, the initial undrained shear strength of the HKMD fill was negligible. After a four-month treatment, a crust layer with the undrained shear strength around 40 kPa was formed. Below the crust layer, the average undrained shear strength reached over 30 kPa, indicating the effectiveness of the preliminary treatment method of using PHDs with vacuum preloading. It should be mentioned that segregation might occurred to some extent at the bottom layer of HKMD fill, which could explain the high shear strength near the bottom. However, further investigation, particularly on filling- or vacuum- induced soil segregation, is needed.

Due to project constraints, the duration of the pilot test was capped at 12 months, including the preparation period and four-month preliminary treatment, to meet the site handover deadline for other construction and development plans. If a longer duration of treatment was allowed, the strength of the treated soil and the thickness of the crust layer would have been further increased. Apart from relying on the formation of crust layer, other solutions, such as sand capping, use of geotextiles, or mixing the surface soil with binders can be adopted to form a working platform for the secondary treatment of the proposed ground improvement method.

To conduct the secondary treatment of the proposed ground improvement method, the fill needs to have sufficient bearing capacity to support crawler machines for installing PVDs. Due to the time restriction, the secondary treatment was not performed. Nonetheless, the undrained shear strength of the HKDM after the four-month treatment was sufficient to support the lightweight construction equipment required for the installation of PVDs for the secondary treatment.

In summary, the results of the pilot test demonstrated the effectiveness of the preliminary treatment of the proposed ground improvement method and the feasibility of using the locally dredged HKMD as fill materials for reclamation.

4 SETTLEMENT CALCULATION

The settlement of the HKMD fill is calculated using the simplified Hypothesis B method proposed by Yin et al. (2022b):

$$S_{totol}(t) = US_f + S_{creep} \tag{1}$$

$$S_{creep} = \begin{cases} \alpha U^{\beta} S_{creep,f} \\ \alpha U^{\beta} S_{creep,f} + (1 - \alpha U^{\beta}) S_{creep,d}, for\ t \geq t_{EOP,field} \end{cases} \tag{2}$$

where US_f is the "primary" consolidation settlement, $S_{creep,f}$ and $S_{creep,d}$ are the "final" creep settlement without considering pore pressure coupling and the creep settlement delayed by pore pressure coupling, respectively. Detailed definition and explanation of Eq. (1) as well as the equations to determine S_f, $S_{creep,f}$, and $S_{creep,d}$ can be referred to Yin et al. (2022).

Chen et al. (2024) proposed a mapping method to consider the consolidation of soft soil improved by PHDs with arbitrary spacings (Figure 5), in which the average degree of consolidation is expressed as:

$$U = 1 - e^{(-8\bar{T}/\bar{\mu})} \tag{3}$$

where $\bar{T} = ct/(2H/i)^2$ is the generalized time factor. For one-way drainage, i = 1; two-way drainage, i = 2. c is a state-dependent coefficient of consolidation and can be determined as:

$$c = \frac{k}{m_v \gamma_w} = \frac{2.3k_i(1+e)\sigma_i'}{C_c \gamma_w} \cdot 10^{\left[(e_i - e)\left(1/C_c - 1/C_k\right)\right]} \tag{4}$$

where σ_i' is the initial effective stress at e_i for normally consolidated soil, C_c is the compression index, and C_k is a coefficient relating change in void ratio to change in permeability:

$$k/k_i = 10^{(e-e_i)/C_k} \tag{5}$$

In this study, C_k = 0.34 was adopted for settlement calculation. $\bar{\mu}$ is a generalized correction factor, which is determined by Eq. (6):

$$\bar{\mu} = \mu_{ps} \cdot \left(4\mu_{ax}/\pi\mu_{ps}\right)^{[(S_h - w_d)/(2H/i - w_d)]} \tag{6}$$

where S_h, w_d, and H, are the horizontal spacing, width, and vertical spacing of PHDs; μ_{ax} and μ_{ps} are the correction coefficients used in the existing axisymmetric unit cell theory method for vertical drains (Hansbo, 1981) and plane-strain theory for soils improved by a drain sheet (Hird et al., 1992).

It should be noted that c, $\bar{T}$, and $\bar{\mu}$ need to be updated according to the updates in void ratio, e, and thickness, H, during the consolidation. A simplified and explicit procedure was adopted to avoid iterations for spreadsheet calculation, as illustrated by Figure 6.

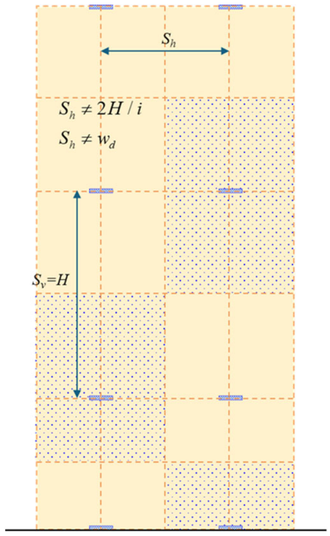

Figure 5. Soft soil improved by PHDs with arbitrary spacing

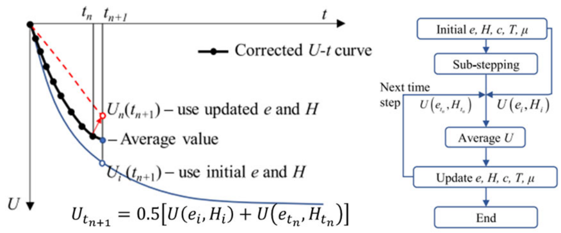

Figure 6. Illustration of the simplified and explicit procedure

After each time-step of calculating average degree of consolidation, the void ratio and thickness of the soil should be updated by $e = e_i - U\Delta\varepsilon_f(1 + e_i)$ and $H = H_i - H_i U \Delta\varepsilon_f$, respectively. $\Delta\varepsilon_f$ is pre-determined strain change under applied load increment. H_i is the initial thickness of a given HKMD fill layer. During each filling of HKMD, the thickness is assumed to increase linearly with time:

$$H_i = \begin{cases} H_{fill} t/t_c, & for\ t < t_c \\ H_{fill}, & for\ t \geq t_c \end{cases} \tag{7}$$

where t_c is the period of a given filling process, H_{fill} is the thickness of a newly filled HKMD with consolidation.

In the pilot test, four layers of HKMD fill were applied. Figure 7 provides an illustration of multi-stage filling with multiple layers of HKMD and PHDs. Each HKMD fill served as a surcharge load to the previously filled HKMD. Stages 1, 2, and 3 represent the filling process for 1st, 2nd, and 3rd layers of HKMD fill, respectively. The filling process of 4th layer of HKMD fill is represented by Stages 4 and 5. In Stage 4, vacuum was only applied to the bottom tow layers of PHDs only, while in Stage 5, vacuum was applied to all four layers of PHDs. The simplified vertical load on each layer used for settlement calculation is plotted in Figure 8(a). Vacuum pressure was applied in Stages 4 (03/09/22-03/18/22) and 5 (04/19/22-07/23/22). The simplified vacuum distributions used for settlement calculation are shown in Figure 8(b). It should be noted that the self-weight consolidation right after the filling of each HKMD layers was not considered in the calculation and the initial void ratio was estimated to be 1.6 under self-weight after deposition (Chen et al., 2024).

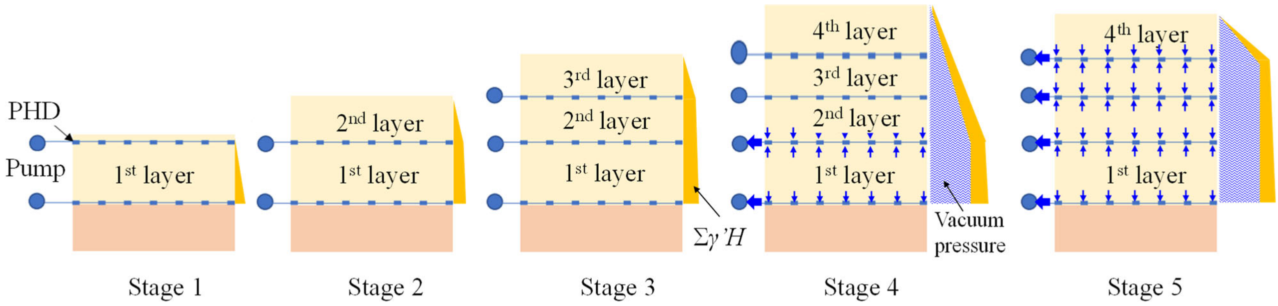

Figure 7. Illustration of multi-stage filling with multiple layers of HKMD and PHDs

HKMD fill treated by multi-layer PHDs with multi-stage vacuum preloading.

For simplification, the 4th HKMD layer was considered as overburden (surcharge load). Therefore, the settlement calculation was performed on 1st, 2nd, and 3rd HKMD layers. The soil parameters used for the calculation are listed in Table 3. The calculated settlements are plotted in Figure 8 together with the measured data. In general, the settlements calculated using the simplified Hypothesis B method agree reasonably with the measured data, demonstrating the applicability of the proposed calculation method.

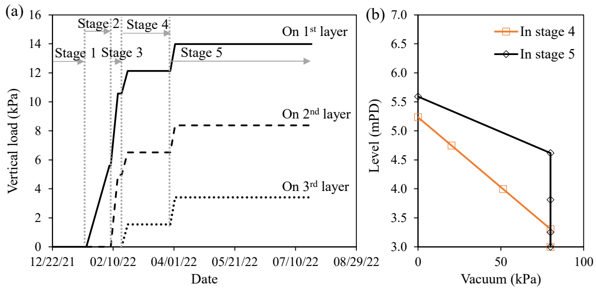

Figure 8. (a) Illustration of multi-stage filling with multiple layers of HKMD and PHDs; (b) Vertical load; and (c) vacuum pressure used for calculation

Table 3. Soil parameters

Parameter	Symbol	Value	Unit
Unit weight	γ_{soil}	16	kN/m^3
Initial void ratio	e_i	1.6	-
Compression index	C_c	0.362	-
Creep coefficient	C_α	0.003	-
Initial permeability	k_i	0.0074	m/d

5 CONCLUSIONS

The results of the pilot test revealed that the water content of the HKMD fill reduced from 150% to 50% and the average undrained shear strength increased over 30 kPa, demonstrating the effectiveness of the preliminary treatment (treating the soil using PHDs with vacuum preloading) of the proposed ground improvement method and the feasibility of using the locally dredged marine sediments as fill materials for reclamation. The simplified Hypothesis B method developed by Yin et al. (2022) and the mapping method proposed by Chen et al. (2024) were successfully applied to predict the settlements of multi-layer

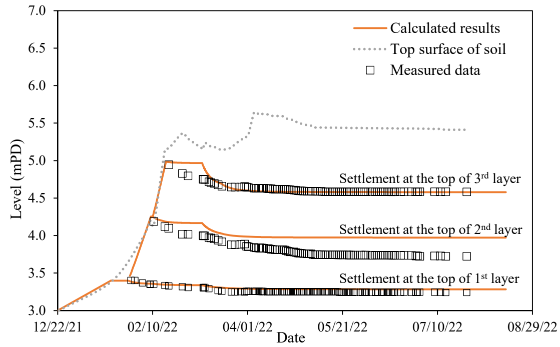

Figure 9. Measured and calculated settlements of 1st, 2nd, and 3rd HKMD layers

6 ACKNOWLEDGEMENTS

The research work is supported by research grants, RIF: R5037-18; GRF: 15226722; RILS: CD7A and CD7J. The authors also would like to express their appreciation for the support and joint efforts of the Sustainable Lantau Office (SLO) and Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) of HKSAR, AECOM, and Build King-Samsung C&T Joint Venture, which contributed to the successful completion of the pilot test.

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