

Effectiveness of soil improvement for deep excavation in under-consolidated soil: A case study

Yoshua Thendar¹, Aswin Lim^{1*}, and Ryan Alexander Lyman¹

¹Department of Civil Engineering, Universitas Katolik Parahyangan, Bandung 40141, Indonesia

Abstract. The main objective of this article is to investigate the effectiveness of soil improvement methods, such as jet grouting and cement deep mixing, for a deep excavation in under-consolidated soil. A well-documented case history, located in Zhuhai, China, was used for analysis. The analyses were conducted using two-dimensional plane-strain finite element analysis. The studies included an examination of the effect of wall length on lateral wall deformation, the effect between the degree of consolidation and lateral wall deformation, and the influence of soil improvement on lateral deformation and settlement. The deformations induced by under consolidating states are greater than those caused by normally consolidated states. A similar trend was found with or without soil improvement. The greater the degree of consolidation is, the smaller the deflection of the wall. In this case, the retaining wall's length is well designed and stable, but the analysis results showed that the wall length can be shorter than the constructed length. Massive jet grouting was used behind the left wall to successfully reduce wall deflection and ground surface settlement. Finally, deep cement mixing has only a small effect on reducing wall deflection and ground surface settlement.

1 Introduction

Due to the shortage of land, land reclamation has become an effective solution to fulfill human needs. Some megacities, such as Shanghai, Shenzhen, Tianjin, Jakarta, Osaka, Chennai, Manila, Tokyo, Karachi, Buenos Aires, Rio de Janeiro, Istanbul, Lagos, Mumbai, Los Angeles-Long Beach-Santa Ana, and Lima, have performed land reclamation on a large scale [1]. In reclamation projects, the main issue is the consolidation settlement of soft clay, which is located on the seabed [2, 3]. Hence, controlling and monitoring consolidation settlement is vital in reclamation projects. Ideally, the reclaimed land is ready to be used when the consolidation settlement is finished or nearly finished (90% consolidation degree), which is challenging to determine. A piezocone is usually used to assess the degree of consolidation in the reclaimed area [4-6]. For some reason, engineers need to start constructing with the soil under a consolidating state [7-9]. In this paper, a deep excavation project under consolidating soil is presented.

For constructing a basement or a shaft, the deep excavation method is well known. In a relatively soft soil and when the depth of excavation is larger than 6 m, a retaining structure must be designed and constructed. Retaining structures include sheet-pile walls, contiguous-pile walls, and diaphragm walls [7, 10-12]. In addition, to increase the retaining wall system stiffness and control the deformations induced by deep excavation, some auxiliary measures could also be adopted, such as jet grouting, deep cement mixing, and the usage of buttress and cross walls [13-18]. These

measures have been reported to be successful in deep excavation projects.

Lim et al [9] reported an excavation depth of 5.25 m at a location in North Jakarta, Indonesia. The retaining wall system used a double-wall system, which consists of corrugated concrete sheet-pile (CCSP) walls with vertical tie-back piles. The CCSP walls and vertical tie-back piles were connected using a tie-beam. In this project, the measured wall deflection was approximately 160 mm and exhibited a cantilever shape. This movement is considerably large, where the normalized maximum wall deflection to excavation depth (d_{hmax}/H_e) is approximately 3.04%. For comparison, in the Tribeca excavation case in Singapore soft clay [19], which has a similar pattern of wall deflection, the ratio is only approximately 1.33%. This large wall deflection is due to the excess pore pressure acting on the wall. Lim et al [9] predicted that the degree of consolidation at the time of excavation was approximately 40%. In this project, no auxiliary measures were planned, so a very large deformation occurred.

Chai et al [7] investigated a deep excavation project under consolidating soft soil in Zhuhai, China. The excavation depth is 13.8 m, and the normalized maximum wall deflection to excavation depth (d_{hmax}/H_e) is approximately 0.3%. In this project, jet grouting and deep cement mixing were used to increase the shear strength of soft soil and reduce the wall deflection and ground surface settlement. These soil improvement techniques are considered successful in controlling the deformations induced by excavation.

In this paper, the effectiveness of soil improvement in excavation is examined [7], especially in

*Corresponding author: aswinlim@unpar.ac.id

underconsolidated soil, where it has not been clearly investigated. Several parametric studies were conducted, such as the effect of wall length on lateral deformation, the effect of the degree of consolidation on lateral deformation, and the influence of soil improvement on lateral deformation and settlement. In addition, the effectiveness of each soil improvement technique applied in the project is also discussed. Some recommendations, such as the effective normalized wall length to excavation depth and an efficient soil improvement method for controlling deformations induced by excavation in underconsolidated soils, are proposed.

2 Methods

2.1 Project description

The excavation project is located on Zhuhai Island, China. The soil was predominantly Holocene alluvial clayey soil. Along the coastal area, land reclamation was conducted, and the reclaimed area was approximately 3 to 5 m thick; the original soil is still consolidated [20]. The purpose of the excavation is to support the Macao-Hengqin Port and Integrated Transportation Hub project.

The braced excavation method was adopted, and contiguous-pile walls were used as the soil retaining wall. The excavation has a width of 58 m and a depth of 13.8 m. Nearby, the Nanguang Project had an excavation area of 112 m × 68 m and a depth of 14.4 m. The excavation of this project commenced after the Nanguang excavation ended. The cross section of the excavation project is shown in Fig. 1. In this excavation, jet grouting and deep cement mixing methods were applied to increase the shear strength of the soft soil. Interested readers can refer to Chai et al. for the details of the field data. and the explanation detail of the field data can be read in Chai et al [7].

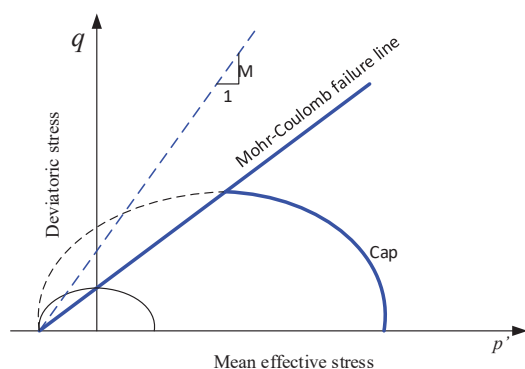


Fig. 1. The yield surface of the soft soil model in p' - q space.

2.2 Soil stratification and modeling

In general, the soil strata were categorized into six categories, with the clay layer dominating. The artificially filled sandy soil layer is 3.7 m thick, followed by the hydraulically filled sandy soil layer, which is 1.2 m thick. A 17.6 m thick clayey mud layer is next,

followed by a 5.9 m thick, muddy clay layer. Then, a 14.7 m thick silty clay layer was found, followed by a gravelly sand layer. The soil profiles and index properties are shown in Fig. 2.

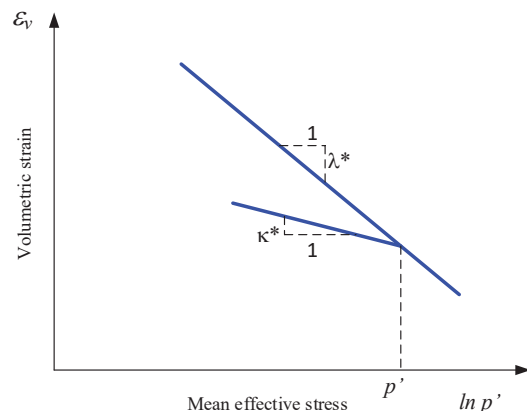


Fig. 2. The logarithmic relation between volumetric strain and mean effective stress.

Two-dimensional finite element analysis is currently a popular and reliable method for modeling excavation problems. The results these analyses have been verified through many case studies [21-26]. The first 4 layers were simulated using the soft soil model (SSM) [27], while the last 2 layers were modeled using the Mohr-Coulomb (MC) model. The yield surface of the soft soil model in p' - q space is depicted in Fig. 3.

Some important features of the soft soil model are stress-dependent stiffness, the distinction between primary loading and unloading-reloading, memory of the preconsolidation stress, and failure behavior according to the Mohr-Coulomb criterion. The parameters λ^* (slope of the virgin compression line), k_v (vertical hydraulic conductivity), e (void ratio), and γ (unit weight) were obtained through oedometer test results. The parameter k_h (horizontal hydraulic conductivity) was assumed to be equal to k_v for the fill layers and the gravelly sand layer, whereas the remainder of the layers were assumed to be $1.5 k_v$. Furthermore, the values of k^* (slope of the unloading-reloading line) were considered to be $1/10$ of λ^* . Fig. 4 shows the logarithmic relation between volumetric strain and mean effective stress.

The parameter c' (effective cohesion) was taken based on the soil properties, and the parameter ϕ' (effective friction angle) was assumed to be 30° for layers using the SSM and 35° for layers using the MC model. The groundwater level was located at -1 m below the ground surface. Fig. 5 shows the finite element mesh for analysis. The soil elements were simulated with a 15-node triangle. The horizontal dimension of the model was larger than 4 times the final excavation depth, and the bottom was set at the hard soil, i.e., 50 m based on the soil investigation. The model's left and right vertical boundary were specified as roller boundaries, and the bottom boundary was set to be fixed. Finally, the soil parameters for each layer are presented in Table 1. In this article, all analyses were conducted using PLAXIS 2D software [27]. The values of the input parameters followed Chai et al [7] because they were well calibrated and validated.

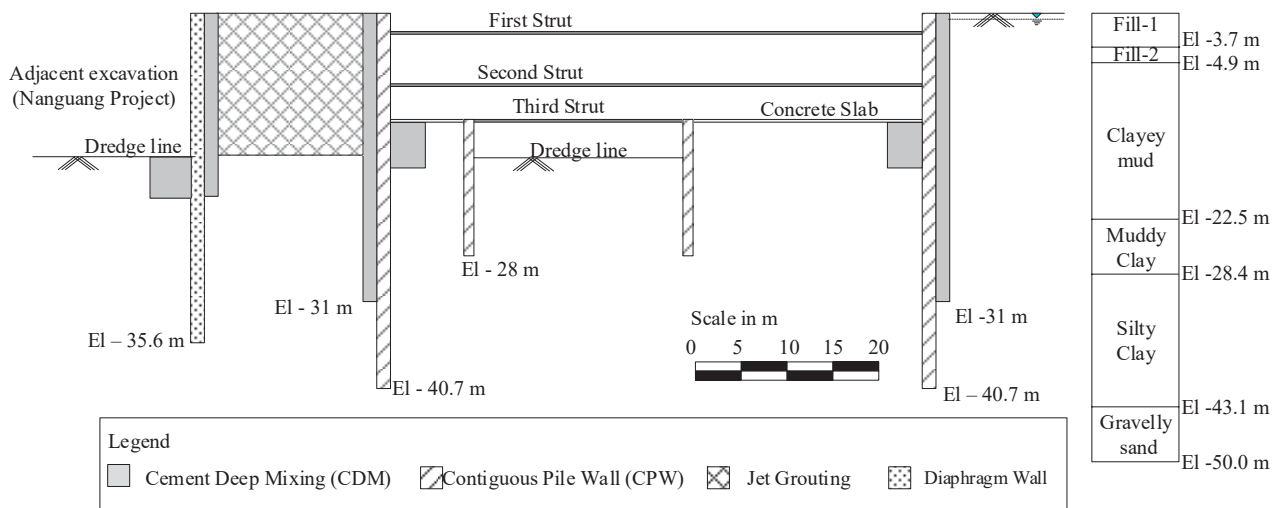


Fig. 3. Cross-section of the excavation project [7].

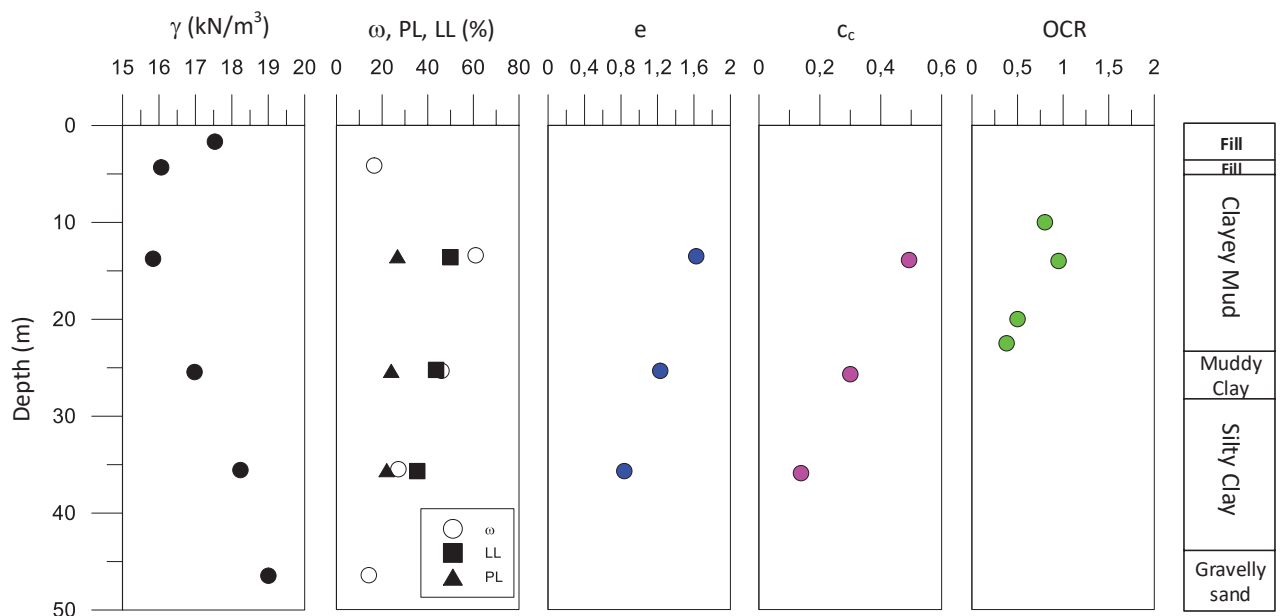


Fig. 4. Soil profile in the project [7].

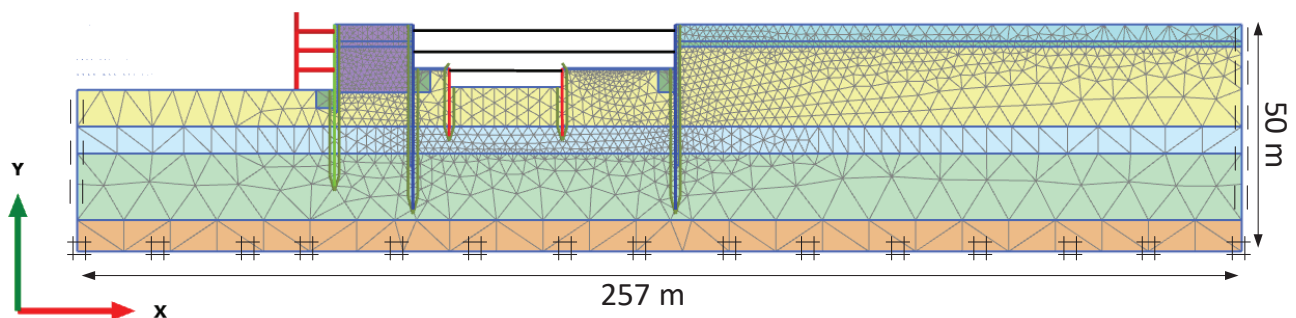


Fig. 5. The finite element mesh for analysis.

Table 1. Soil input parameters for analysis.

Depth (m)	Soil description	γ (kN/m ³)	c' (kPa)	ϕ' (°)	E (MPa)	ν	λ^*	k^*	e	k_v (m/day)	k_h (m/day)	OCR
0 - 3.7	Fill - 1	17.6	15	30	-	0.2	0.022	0.002	1.06	0.43	0.43	8
3.7 - 4.9	Fill - 2	16.2	10	30	-	0.2	0.018	0.002	1.54	0.43	0.43	1.7
4.9 - 22.5	Clayey mud	15.9	8	30	-	0.2	0.079	0.008	1.66	3.7E-05	5.6E-05	-
22.5 - 28.4	Muddy clay	17	8	30	-	0.2	0.018	0.002	1.26	1.7E-04	2.6E-04	-
28.4 - 43.1	Silty clay	18.2	10	35	400	0.2	-	-	0.92	0.0086	0.013	-
43.1 - 50	Gravelly sand	19	10	35	600	0.2	-	-	0.76	1	1	-

2.3 Structural elements

2.3.1 Contiguous pile walls and diaphragm wall

In this model, contiguous pile walls (CPWs) and a diaphragm wall were modeled as plate elements. There were 2 types of CPWs: the main CPW and the inner CPW. The main CPW has a diameter of 1.5 m, whereas the inner CPW has a diameter of 1.2 m. The main CPW has two main reinforcement configurations: the left one has 44 longitudinal bars (32 mm in diameter), and the right one has 36 longitudinal bars (40 mm in diameter). The main reinforcement for the inner CPW has 16 longitudinal bars (32 mm in diameter). Both types of CPW have hoop bars that are $\phi 25@2000$ (25 mm diameter with 2000 mm spacing) and spiral hoop bars that are $\phi 12@100$ for the main CPW and $\phi 12@120$ for the inner CPW.

Furthermore, the main CPW has enhanced hoop bars $\phi 25@2000$ and an ultrasound checking tube that is 57 mm in diameter and 3.5 mm in thickness. Moreover, the diaphragm wall represents the soil retaining wall for the Nanguang Project. Table 2 summarizes the parameters for these elements. For the pile, C35 concrete with a design compressive strength of 16.1 MPa and a Young's modulus of 31500 MPa was used. In addition, a 0.3 m thick concrete slab is located 9.6 m underground. It has a compressive strength of 25 MPa, its unit weight was taken as 24 kN/m³, and it has a Poisson ratio of 0.15.

2.3.2 Struts

The three struts were made of reinforced concrete beams and were designed to offer lateral support to the wall. All three feature a horizontal spacing of 9 m, four 12 mm diameter hoop bars with 100 mm spacing in the weak zone and 200 mm spacing in the normal areas, and 32 mm longitudinal bars. The first and third struts contain 26 longitudinal bars each, whereas the second

and fourth struts have 38. They also have the same modulus of 31500 MPa and cross-sectional areas of 0.133 m² for the first strut and 0.16 m² for the second and third struts.

Table 2. Input parameters for deep cement mixing.

Type	Depth (m)	Thickness (m)	E (kPa)	ν
Behind the main CPW	31	0.78	50000	0.15
Behind the diaphragm wall	19.2	0.7	50000	0.15
In front of the main CPW	5	3.85	50000	0.15
In front of the diaphragm wall	4	4	50000	0.15

2.4 Soil improvements

Within this model, soil improvement is accomplished through the use of a cement deep mixing (CDM) column and jet grouting. These improvements were made before the start of the excavation. The jet grouting comprises 0.8 m diameter columns that form a 3.4 m $\times$ 3.4 m grid that reaches a depth of 15 m and a width of 15.14 m. The jet grouting concrete has a Young's modulus of 20 MPa. In CDM, each column is 0.85 m in diameter and 5 m in length, with a 0.6 m overlapping gap.

This model has four CDM columns, which are located in front of and behind the main CPW and the diaphragm wall. This was done to improve the stability of the main excavation. Jet grouting and CDM were both modeled as soil clusters with a linear-elastic material and nonporous drainage. The concrete in both upgrades has a unit weight of 24 kN/m³ and a Poisson ratio of 0.15. Table 3 displays the features of each CDM column. The details of the structural components can be found in Chai et al [7].

Table 3. Input parameters for contiguous pile walls and diaphragm wall.

Type	Depth (m)	Thickness (m)	Spacing (m)	E (kPa)	A (m ²)	I (m ⁴)	EI (kPa/m)	EA (kN/m)
Main CPW	40.7	1.21	1.7	37600	1.76	0.147	3265230	39085109
Inner CPW	15	0.93	1.5	34500	1.13	0.067	1541684	26012387
Diaphragm wall	35.6	0.8	-	37600	0.8	0.043	1604267	30080000

3 Stage construction

In general, the analyses consisted of two scenarios. First, the initial condition of soil stress is normal consolidated, and second, the initial condition of soil stress is under consolidated. To establish an underconsolidated state, the following procedure was adopted [7]:

- Determine the most recent loading history at the project location. For this study, it was assumed that the reclamation was completed 30 years before the building.
- Calculate the initial condition of the soil.

- Run a coupled consolidation analysis from the initial loading time to the present using the recently added fill. The added fill in this example is 4.9 m, and the loading time is 30 years.

- The displacement was reset to zero, but the calculated stresses remained from the previous phase.

Then, the excavation stages were as follows:

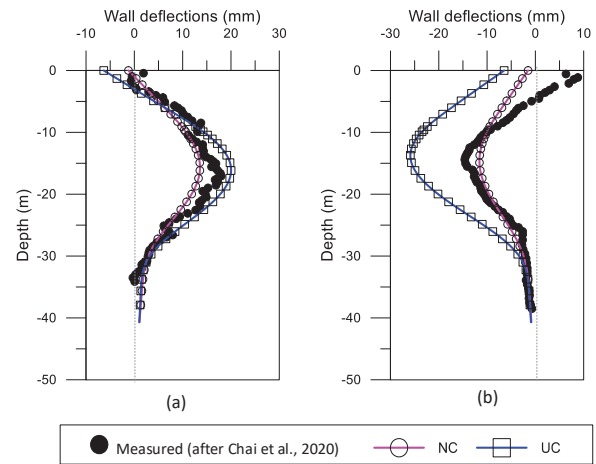
- Install the diaphragm wall and implement deep cement mixing for the Nanguang project.
- The 1st excavation for the Nanguang project (EI - 2.5 m).

- Install the 1st strut (El. -1.5 m) for the Nanguang project.
- The 2nd excavation for the Nanguang project (El - 7.7 m).
- Install the 2nd strut (El. -5.7 m) for the Nanguang project.
- The 3rd excavation for the Nanguang project (El - 11 m).
- Install the 3rd strut (El -10 m) for the Nanguang project.
- The 4th excavation for the Nanguang project (El - 14.4 m).
- Apply jet grouting next to the excavation of the Nanguang project.
- Reset the displacement to zero.
- Install the main contiguous-pile walls and implement cement deep mixing for this projectThe 1st excavation for this project (El -2.3 m).
- Install the 1st strut (El -1.3 m) for this project.
- The 2nd excavation for this project (El -7.0 m).
- Install the 2nd strut (El -6.0 m) for this project.
- The 3rd excavation for this project (El -9.6 m).
- Construct the concrete slab.
- Install the inner contiguous-pile walls.
- The 4th excavation for this project (El -11.2 m).
- Install the 3rd strut (El -10.2 m) for this project.
- The 5th excavation for this project (El -13.8 m).

For the normally consolidated state, stages a to d were not performed, and they were replaced with the K₀-procedure with an overconsolidation ratio equal to 1 for all soils.

4 Results and discussion

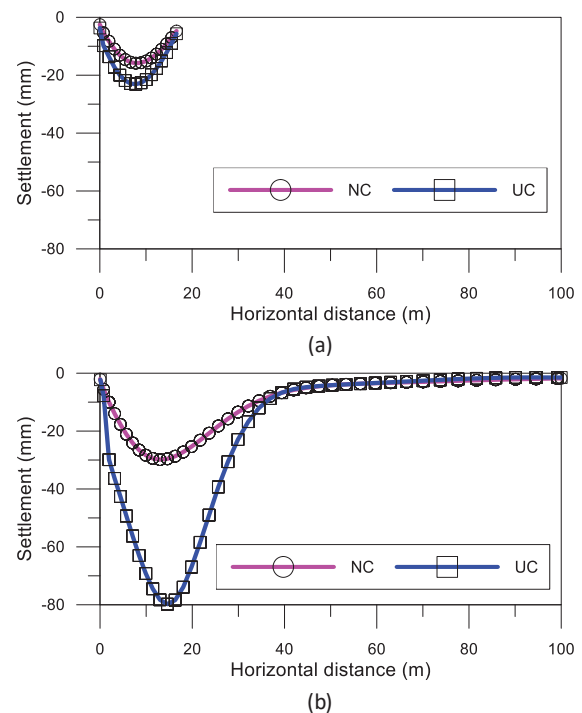
Fig. 6 shows the comparison of the measured and computed wall deflections. Notably, the lateral wall deflection shown in Fig. 6 is the incremental value from the installation of the second strut to the implementation of the final excavation. The underconsolidated state yields a higher maximum lateral deformation than the normally consolidated state for both sides of the wall. For the left wall, the computed maximum wall deflections for normally consolidated and under consolidating states are 14 mm and 20 mm, respectively. Meanwhile, for the right wall, the computed maximum wall deflections for normally consolidated and underconsolidated states are 12 mm and 26 mm, respectively. For the left wall, the underconsolidated state could yield a close result to the measured data. Moreover, for the right wall, the normally consolidated state yielded a closer result to the measured data. Both walls have a similar trend, in which the underconsolidated state yields a higher value than the normally consolidated state. However, the left side has a smaller value due to jet grouting improvement.



*NC and UC donate normally consolidated and under consolidating, respectively.

Fig. 6. Comparison of measured and computed incremental wall deflections from the installation of the second strut to the final excavation (a) left wall (b) right wall.

Fig. 7 shows the comparison of computed surface settlements in normally consolidated and underconsolidated conditions. It is obvious that the under consolidation yields a larger ground surface settlement. For the location behind the left wall, the difference between normally consolidated and underconsolidated is approximately 4 mm. Meanwhile, for the location behind the right wall, the difference between normally consolidated and underconsolidated is approximately 50 mm. Hence, it could be concluded that the application of jet grouting behind the left wall could minimize the effect of underconsolidated soil on the deformation induced by excavation.



*NC and UC donate normally consolidated and under consolidating, respectively.

Fig. 7. Comparison of computed surface settlements at normally consolidated and under consolidating conditions: (a) behind left wall and (b) behind right wall.

5 Parametric study

To understand the mechanism and effect of soil improvement on deformation, a series of parametric

studies was conducted. All stage construction for the parametric study followed the original model with variations that are listed in Table 4.

Table 4. Scenario of parametric study.

Parameter	Variable	Soil State	Objective
Length of Contiguous Pile Wall	35 m, 40 m, 45 m	Normally-consolidated (NC), Under-consolidating (UC)	To examine the effects of pile length on lateral deformation
Degree of Consolidation of Clayey Mud layer	10%, 25%, 50%, 75%, 90%	Under-consolidating (UC)	To examine the relationship between the degree of consolidation and lateral deformation
Soil Improvement	No Soil Improvement, CDM only, CDM and Jet Grouting	Normally-consolidated (NC), Under-consolidating (UC)	To investigate the influence of soil improvement on lateral deformation and ground settlement

The parametric study was performed both at normally consolidated and underconsolidated states. First, the length of the contiguous-pile wall was varied from 35 m, 40 m, and 45 m to examine the effects of pile length on lateral deformation. Second, the degree of consolidation was varied to investigate the relationship

between the degree of consolidation and lateral deformation. Third, the existing soil improvement methods were varied to investigate the influence of soil improvement on lateral deformation and settlement. Fig. 8 depicts the model scheme for the parametric study.

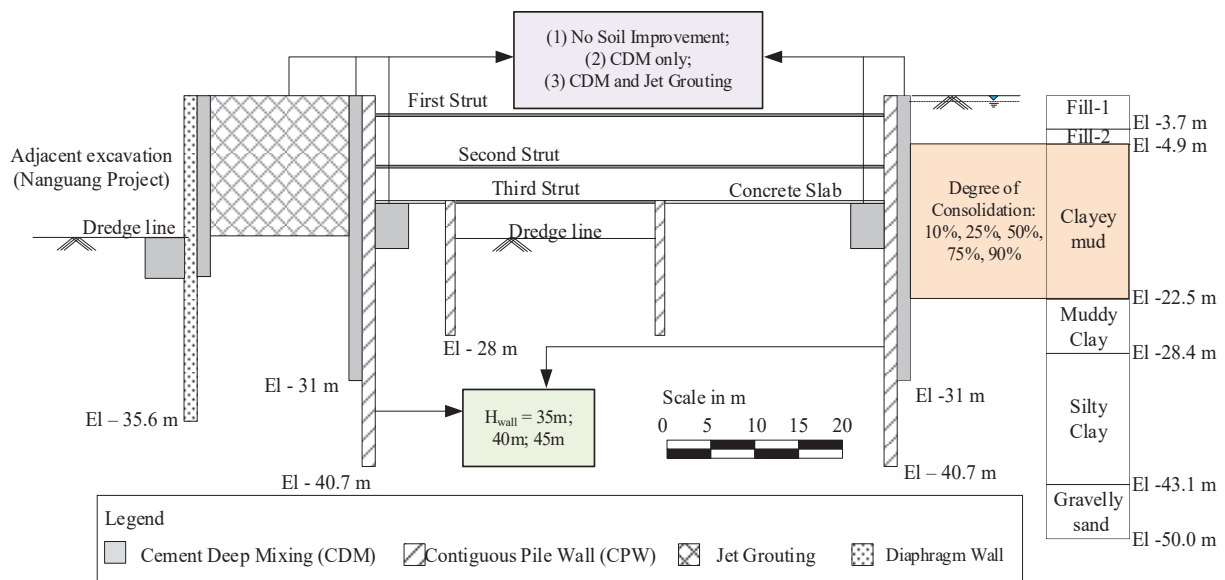


Fig. 8. Model scheme for parametric study.

5.1 Effect of contiguous-pile wall lengths

Fig. 9 depicts the result of varying contiguous-pile wall lengths. It is observed that for identical conditions, the results overlapped for both left and right walls. This indicates that, in this case, the original design length (40 m) is adequate to control the wall deformation. The wall is in a stable condition.

The ratio between the wall penetration depth and final excavation depth (H_p/H_e) is 1.9. This value is considered a conservative number. In common practice, to reach a stable wall condition, H_p/H_e is approximately 1.8 [9]. In addition, it is also possible to reduce the pile wall length to 35 m because it yielded similar deflection with the 40 m pile wall length. Again, in an underconsolidated state, the wall yielded a larger wall deflection.

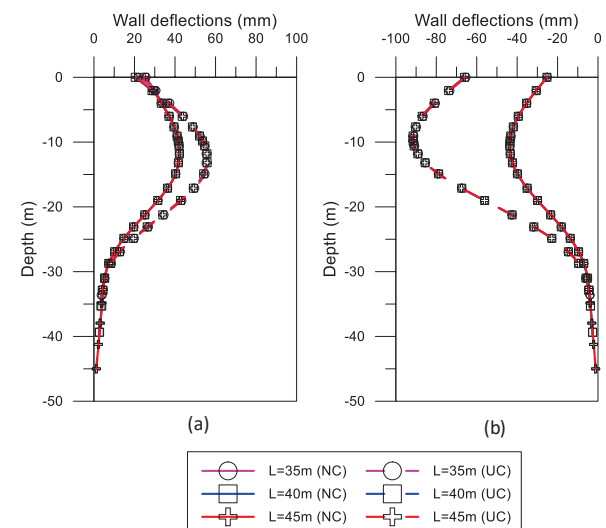


Fig. 9. Comparison of wall deflection with different wall length: (a) left wall and (b) right wall.

5.2 Effect of the degree of consolidation in clayey mud layer

Fig. 10 displays the comparison of wall deflections with different degrees of consolidation. The larger the degree of consolidation is, the smaller wall deflection. This is because the excess pore pressure acting on the wall is smaller at a larger degree of consolidation. In addition, the increment of wall deflection between the left and right walls is different.

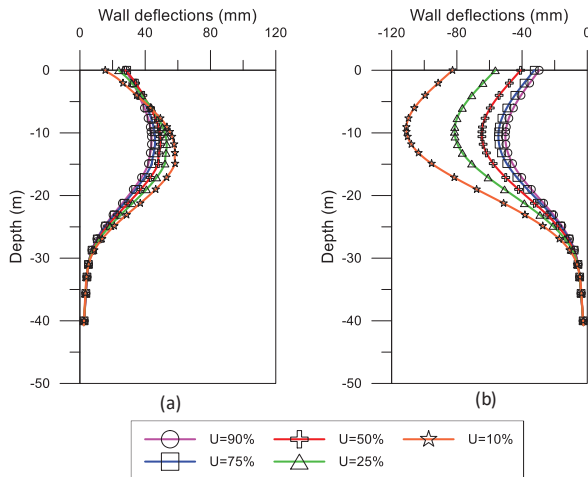


Fig. 10. Comparison of wall deflections with different degree of consolidation: (a) left wall and (b) right wall.

The increment of wall deflection in the left wall is smaller than the increment of the right wall. This is because behind the left wall, a massive jet grouting was applied; hence, the soil shear strength increases significantly to the soil behind the right wall. Hence, it can also be concluded that the effect of an under consolidating state is smaller for hard soil than for soft soil. The same phenomena were also reported by Lim et al [9]. Further investigation of the effect of soil improvement is explained in the next section.

5.3 The influence of soil improvement on lateral deformation and ground settlement

Fig. 11 depicts the comparison of wall deflections with different soil improvement installations. For the left wall, the combination of CDM and jet grouting clearly reduced the wall deflection significantly, both at a normally consolidated state and an underconsolidated state. For normally consolidated and underconsolidated states, the combination of CDM and jet grouting can reduce the maximum wall deflection by approximately 32% and 43%, respectively. Furthermore, if the jet grouting was neglected, then the maximum wall deflection could only decrease to 9% and 13% for underconsolidated and normally consolidated states, respectively. For the right wall, because no jet grouting was installed behind the right wall, the wall deflection could only be reduced by approximately 17% and 12% for normally consolidated and underconsolidated states, respectively. Here, it is obvious that the jet grouting behind the left wall plays an important role in controlling the wall deflections.

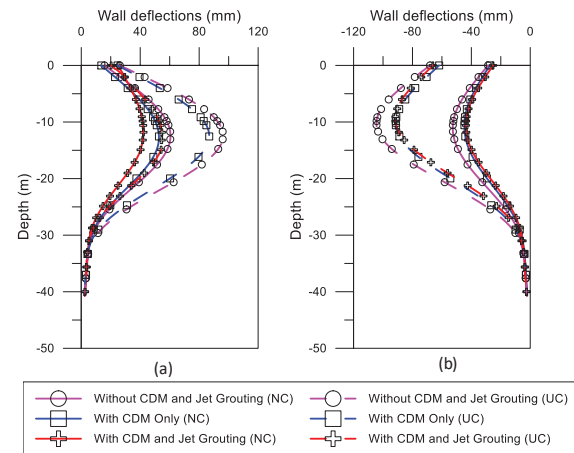


Fig. 11. Comparison of wall deflections with different soil improvement installation: (a) left wall and (b) right wall.

Fig. 12 shows the comparison of ground surface settlement with different soil improvement installations. For surface settlement behind the left wall, the existence of CDM and jet grouting could significantly reduce the ground settlement. The amount of reduction is approximately 77.5% and 82% for normally consolidated and underconsolidated states, respectively. Meanwhile, if the jet grouting was neglected and only relied on the CDM, then the settlement reduction was only 14% and 10% for normally consolidated and underconsolidated states, respectively. The ground surface settlement behind the right wall resembles a concave settlement profile [28]. Because no jet grouting was installed behind the right wall, the ground surface settlement could only be reduced by approximately 14% and 13% for normally consolidated and underconsolidated states, respectively. Again, the application of jet grouting behind the left wall is very effective in controlling the ground surface settlement, both in underconsolidated and normally consolidated states.

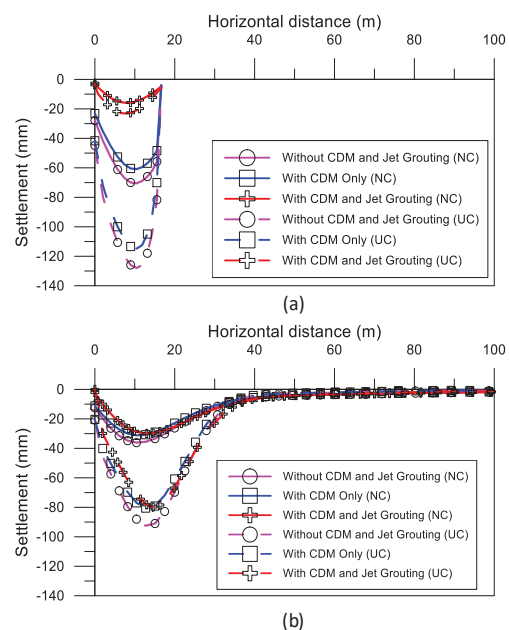


Fig. 12. Comparison of ground surface settlement with different soil improvement installation: (a) behind left wall and (b) behind right wall.

Fig. 13 depicts the comparison of the normalized maximum wall deflection with different wall lengths and the existence of ground improvement. The normalized maximum wall deflection equals 0.5, which is considered a common value for deep excavation in clay [11-12]. For the left wall in the normally consolidated state, δ_{hmax}/H_e is smaller than 0.5 with various wall lengths, which means that ground improvement is not necessarily needed. However, for the left wall in the underconsolidated state, it is obvious that ground improvement is needed because δ_{hmax}/H_e is larger than 0.5 with various wall lengths. If the ground improvement is installed, then δ_{hmax}/H_e decreases than 0.5. Furthermore, in this case, the wall length could be reduced from 40.7 m to 25 m. This finding is significant from an economical design point of view. With a massive ground improvement (CDM and jet grouting), a reduced pile wall length could be economical. For the right wall in the normally consolidated state, the finding is similar to that of the left wall. Hence, since this case is constructed in normally consolidated soil, it is obvious that no ground improvement is needed. For the right wall in the under consolidating state, δ_{hmax}/H_e is still larger than 0.5, although ground improvement with CDM was installed in the field. This indicates that the effectiveness of CDM in this case is not significant.

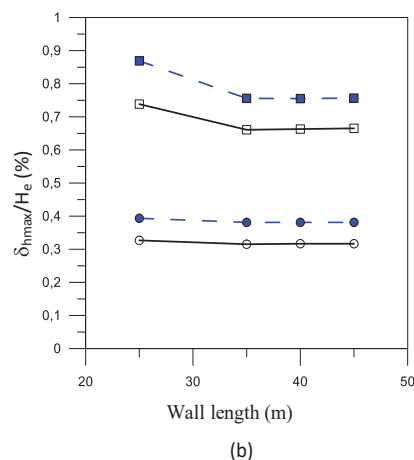
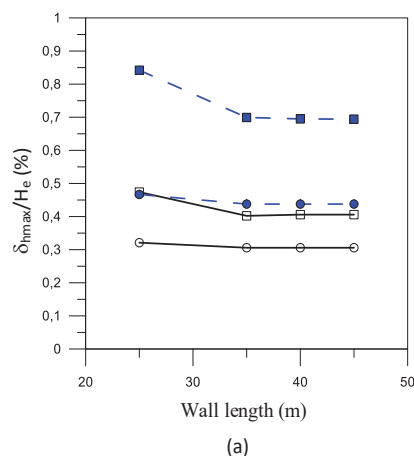


Fig. 13. Comparison of normalized maximum wall deflection with different wall length and the existence of the ground improvement: (a) left wall and (b) right wall.

For similar case conditions, it is suggested that the CDM be neglected. In addition, the length of the retaining wall could be shorter than the common design, where jet grouting is massively constructed behind the retaining wall. These two findings are beneficial for future design considerations for reducing construction costs.

6 Conclusions

This paper investigates the effect of soil improvement on deep excavation in underconsolidated soil. A well-documented case study was simulated using two-dimensional finite element analysis. A series of parametric studies was carried out to evaluate the performance of some factors, such as the length of the retaining wall, the degree of consolidation of the consolidation soil layers, and the effectiveness of the soil improvement (cement deep mixing and jet grouting) application. The results are summarized as follows:

1. The wall deflection and ground surface settlement were successfully controlled by the soil improvement methods used in the construction, namely, jet grouting and cement deep mixing.
2. From the finite element analysis, the deformations induced by underconsolidated states are larger than those of the normally consolidated state. A similar trend is also observed with or without soil improvement. The smaller the degree of consolidation is, the larger the wall deflection.
3. In this project, the length of the retaining wall is well designed and stable. However, the left wall could be shorter due to massive ground improvement behind the wall. The reduction of 15 m of the left wall length did not affect the computed wall deflections.
4. The application of massive jet grouting behind the left wall effectively and successfully controlled the wall deflection and ground surface settlement. Furthermore, cement deep mixing only causes a minimal effect on controlling the wall deflection and ground surface settlement.

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