Performance and modeling of secant pile reinforced by soil nailing for urban excavation in Jakarta

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ABSTRACT

This article presents an excavation case which is located in Jakarta, Indonesia. It adopted secant piles reinforced by soil nailing as the retaining wall system. The excavation area is ± 3673 m^2 and the average excavation depth is 12.0 m. The predominant soil was silty clay with a soft to medium consistency. Besides the standard soil investigations, Pressuremeter test also performed to measure the in-situ soil modulus accurately. In addition, the wall deformations were well monitored with Inclinometer. Later, a 2D finite element analysis was conducted to investigate the performance of the retaining wall system. The soil was modeled with the hardening soil model. The results showed that the measured soil modulus obtained from Pressuremeter could be used a basis for determining soil modulus input parameters, rather than using empirical correlations. The shape of wall deflection was a cantilever shape and the maximum wall deflection was 45 mm. Also, the computed wall deflection was agreed with the measured data. Moreover, the parametric study on the soil nailing length and inclination also conducted to investigate the deformation characteristic of this retaining wall system.

Keywords: Pressuremeter, Soil modulus, Secant pile, soil nailing, Finite Element Method, Excavation

1 INTRODUCTION

Excavations in South Jakarta area are usually constructed with a combination of secant piles and soil anchors or soil nailing. Despite this retaining wall system is relatively cheaper than braced excavation methods, soil conditions in South Jakarta also relatively good compared with soil conditions in North Jakarta. For an excavation analysis, besides the soil shear strength, the soil modulus is a predominant parameter that controlling the deformations induced by excavation (Lim and Ou, 2017). In common practices, the soil modulus for designing an excavation was obtained from an empirical correlation, for example, the correlation to the N_{SPT} values ($E = \beta \times N$). Although the standard penetration test (SPT) procedure has been standardized (ASTM D1586), but the accuracy is operator dependent. Since the value of β is empirical and the N value is inconsistent, the determination of soil modulus becomes challenging. Most of the time, different consultants have different opinions about the value of β, and yields different design of excavation methods. In the project owner point of view, the cheapest and safest excavation method is a priority to be selected.

Pressuremeter is one of in-situ testing for soil where a cylindrical flexible membrane is expanded inside a borehole. Pressuremeter enters the soil by pre-boring a hole into which the probe is placed. Once in the soil, increments of pressure are applied to the inside of the membrane forcing it to press against the soil and so loading a cylindrical cavity. The output of this test is a radial stress-strain curve. One of the advantages of Pressuremeter test is the avoidance of empiricism in deriving soil properties. The obtained fundamental soil parameters if the test reaches plastic zone are the ground pressure at rest (P_0), the yield pressure (P_y), the elastic modulus (E_M), the shear modulus (G_M) and the undrained shear strength (S_u). Pressuremeter and the schematic test is illustrated in Fig 1. The main objective of this paper is to demonstrate the significance of Pressuremeter test in determining soil modulus, in which it is an important soil parameter in an excavation modeling. Later, an excavation case was analyzed thoroughly via PLAXIS 2D and the performance of the retaining wall system was investigated.

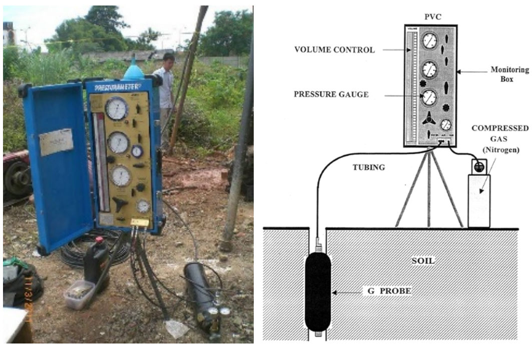

Fig. 1. Pressuremeter device and the testing scheme

2 PROJECT DESCRIPTION

An excavation project was located in South Jakarta, the capital city of Indonesia, where it was bordered by Kali Baru River at East and with the main road at West.

This project consisted of 3 levels of basement and 19 stories of upper structures. The average excavation depth was 12 m. The earth retaining wall system was contiguous bored-pile with 800 mm diameter and 1200 mm spacing (center to center) with the effective length was 23.5 m. In addition, soil nailing with 12 m length was installed behind the retaining wall with an inclination of 30° and 45°, as illustrated in Fig 2, and they were connected by a waler beam. Moreover, Fig 3 shows the excavation location and geometry.

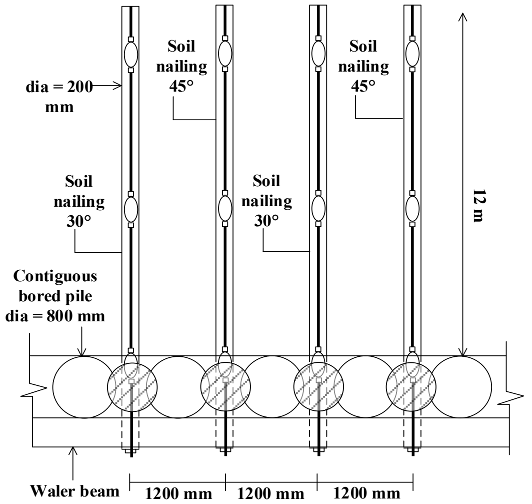

Fig. 2. The arrangement of secant piles and soil nailing

Fig. 3. Excavation location and geometry

2.1 Soil Stratification

According to two bore holes, the soil stratifications could be classified as follow: First layer (0 m - 5 m) was silty clay with a medium consistency. This layer might be an overly consolidated layer due to the desiccation process. The second layer (5 m - 20 m) was silty clay with soft to medium consistency. Starting from GL -20 m, it was a silty sand layer. As indicated by the site investigation, the soil parameters obtained via SPT and laboratory tests are summarized in Fig. 4. In addition, the groundwater level was observed at GL -10 m.

2.2 Result of Pressuremeter Test

Table 1 summarizes all of the measured and interpreted values from Pressuremeter test. In total, four tests were conducted, that were at GL -6 m, GL -12 m, GL -18 m, and GL -24 m. All of the tests indicated soils had reached plastic zone. The highest limit pressure was 30 kg/cm^2 which were measured at the cemented silty sand layer (GL -24 m). Meanwhile, for silty clay with medium consistency (GL -12 m and GL -18 m), the limit pressure was in the range of 9 to 10 kg/cm^2. In addition, the limit pressure measured at GL -8 m was 4.5 kg/cm^2

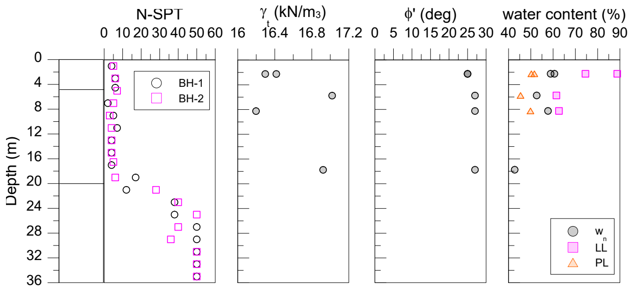

Fig. 4. Typical soil profiles and its parameters

Table 1. Summary of the measured and interpreted values from Pressuremeter tests

No	Depth (m)	NSPT	P_O (kPa)	P_Y (kPa)	P_L (kPa)	E_M (kPa)	s_u (kPa)	K_0
BH-01	6.5-7.5	2	73.5	170.6	451.1	6544.0	68.6	0.72
	12.0-13.0	7	179.5	558.0	1029.7	17756.9	154.9	0.89
BH-02	18.0-19.0	6	208.9	545.2	907.1	34193.8	126.5	0.57
	24.0-25.0	50	416.8	1784.8	3824.6	165390.1	601.1	1.14

Furthermore, Figs 5a and 5b depict the value of OCR and Soil Modulus along with depth, respectively. The original OCR data were calculated from 4 sets of Oedometer test, and the rest were estimated as $OCR = k_s \times p_a \times (\sigma_v' / N_{SPT})$ (Mayne and Kemper, 1988), where k_s is constant from 1.0 to 0.2, and p_a is atmospheric pressure. In this project, the k_s value was 0.5, considering the trend of calculated OCR from Oedometer test. For the soil modulus (E_M), for data were measured directly from Pressuremeter test, meanwhile, the rest were evaluated from an empirical correlation which is E_M = (1500 to 2800 N_{SPT}) with unit kPa. It should be noted that the E_M used for analysis was carefully evaluated according to the measured and empirical data as shown in Figs 5a and 5b, respectively. Indeed, the N_{SPT} below 24 m were mostly larger than 60 and no exact value of N_{SPT} was recorded. Hence, the E_M obtained from the empirical correlation might not accurate for the depth below 24 m. As a consequence, by engineering judgment, following the data trend of E_M which was measured from the PMT test seems more reasonable.

2 FINITE ELEMENT MODELING

The PLAXIS 2D finite element program was used to model the excavation project. Fig 6 depicts the finite element mesh and the model boundary. The excavation depth was 12 m, and the excavation width was 44 m. The analysis was followed by the cross section in which the inclinometer casing was located.

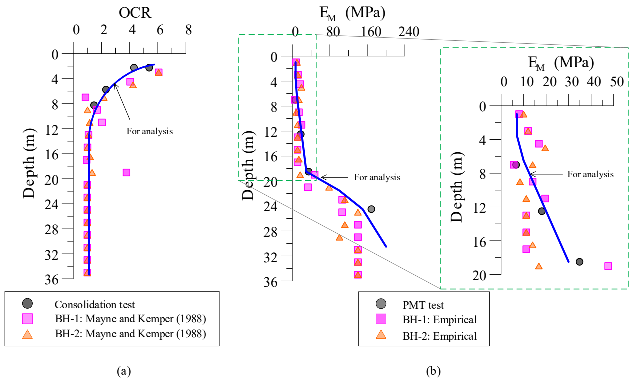

Fig. 5. (a). The OCR and (b). Soil modulus values for analysis

Only half of the excavation geometry was adopted in the analyses due to symmetry. The soil movements were fixed at the bottom of the boundary and restrained at the vertical direction for both sides. In addition, the distance between the retaining system and the outer boundary of mesh was ensured to be larger than $2H_e$ (final excavation depth) to minimize boundary effects. Moreover, fifteen-node triangular elements were used to simulate the soil cluster, 5-node plate elements were used to model the retaining system and 10-node interface element was applied to model the soil-plate element interaction behavior. The behavior of interface friction (R_{inter}) between the structural elements and adjacent soils follows the Mohr-Coulomb model

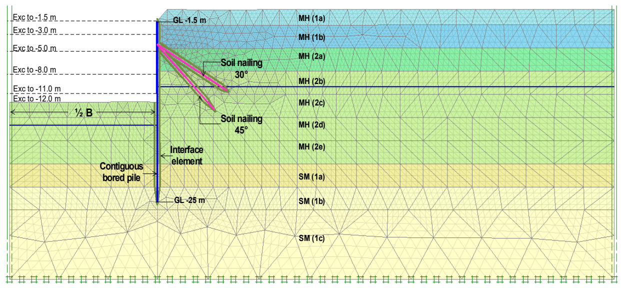

Fig. 6. Typical finite element mesh and boundary used for analysis

3.1 Soil Constitutive Model, Model Parameters and Structural Parameters

The Hardening Soil (HS) model (Schanz et al., 1999), an advanced hyperbolic soil model formulated in the framework of isotropic hardening double surface plasticity, was adopted to simulate the soil behavior. It required eleven material parameters ($c', \phi', \psi, E_{50}^{ref}, E_{oed}^{ref}, E_{ur}^{ref}, m, \upsilon_{ur}, p^{ref}, K_o^{NC}, R_f$) and is summarized in Table 2. Due to page limitation, the derivation of input parameters was not shown here.

Table 2. Summary of the measured and interpreted values from Pressuremeter tests

Depth (m)	Analysis type	γ_t (kN/m³)	ϕ' (°)	c' (kPa)	OCR	E_{50}^{ref} (kPa)	E_{oed}^{ref} (kPa)	E_{ur}^{ref} (kPa)	m	νur
0 - 5	Undrained	16.5	27	0	5	8658 - 18689	6061 - 13082	25974 - 56067	1	0.2
5 - 20	Undrained	16.5	30	0	1 - 2	14345 - 27043	10041 - 18930	81130 - 43034	1	0.2
20 - 35	Drained	18	35	0	1	97590 - 171062	97590 - 171062	292771 - 513186	0.5	0.2

The structural members, such as the contiguous bored pile and soil nailing were assumed to behave as linear-elastic. The input parameters are listed in Table 3. The equivalent Young's modulus of soil nailing was calculated according to the fundamentals of material strength as shown in Eq. (1).

$$E_{eq} = E_{nail}\left(\frac{A_{nail}}{A_{total}}\right) + E_{grout}\left(\frac{A_{grout}}{A_{total}}\right) \tag{1}$$

Table 3. Structural input parameters for analysis

Model	diameter (mm)	spacing (m)	EA (kN/m)	EI (kNm²/m)
Contiguous Borpile	0.8	1.2	13210000	528300
Soil nailing	0.2	2.4	472500	1181
*) Soil nailing	0.2	1.2	945000	2362

*) For the parametric study

4 RESULT AND DISCUSSION

4.1 Secant Pile Deflection and Ground Settlement

Fig 7 shows the comparison between measured and computed secant pile deflections for this project at the 2nd stage, 4th stage and final stage of excavation, respectively. It was clearly shown that the computed secant pile deflection yielded a close result with the measured secant pile deflection.

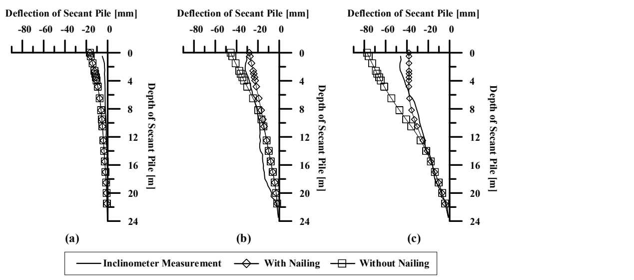

Fig. 7. Comparison of measured and computed deflections at (a) 2nd stage, (b) 4th stage and (c) final stage of excavation

At the final stage of excavation, maximum measured and computed secant pile deflections were 45 mm and 40 mm, respectively. Both wall deflections yielded a cantilever shape of deflection. It implies that the selection of input parameters and the modeling procedure could reflect the field condition. One thing should be emphasized is the soil modulus parameters which were obtained from Pressuremeter test is quite accurate to capture the deformation characteristic of the secant pile.

Furthermore, an analysis was performed to check the effectiveness of the installed soil nailing. If the soil nailing were not installed, the maximum secant pile deflection and ground settlement increased double to around 80 mm and 50 mm, respectively. This indicates the installed soil nailing worked properly and has a significant effect in reducing the wall deflection.

4.2 Effect on Soil Nailing Inclination

The parametric studies were conducted by varying the inclination of the soil nailing into 0°, 15°, 30°, 45° and 60° under the condition of a constant length of soil nailing (L=12 m). In the analyses of parametric study, the inclination of soil nailing was assumed similar for each soil nailing for ease of results interpretation.

Fig 8 shows the deflection and ground settlement with various soil nailing inclination. It was clear that the effective soil nailing inclination was 30° because it yielded the minimum value of secant pile deflection and ground settlement. It seems that the effective inclination angle has a correlation with the internal friction angle of the soil. Future study needs to be conducted for clarifying this presumption.

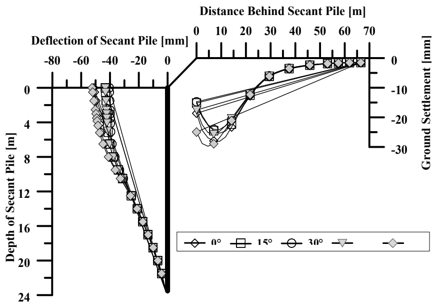

Fig. 8. Secant pile deflection and ground settlement with several inclinations of soil nailing

4.3 Effect of Soil Nailing length

The parametric studies were conducted by varying the length of the soil nailing under the condition of constant inclination at 0°, 15°, 30°, 45°, and 60°. Due to space limitation, only 30° inclination would be discussed. The same as previous parametric studies, the soil nailing inclination in all secant piles are considered to have the same value.

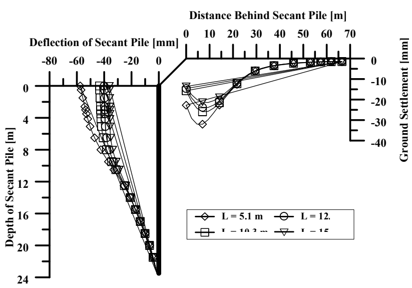

Fig. 9. Secant pile deflection and ground settlement due to length variation effect of soil nailing at 30° inclination

As shown in Fig 9, the increase of soil nailing length would reduce the deformations induced by excavation. In addition, Fig 10a and 10b summarize the parametric results in term of the normalized wall deflection and normalized ground settlement to the normalized length of soil nailing, respectively. It was obvious that 30° inclination and the longer length of soil nailing would yield a smaller deformation induced by excavation.

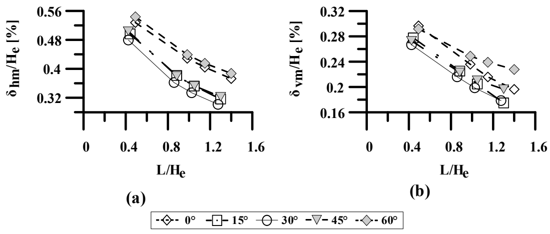

Fig. 10. (a) Normalized maximum secant pile deflection to the normalized soil nailing length and (b) Normalized maximum ground settlement to the normalized soil nailing length

5 CONCLUSIONS

Based on the performed analyses, the following conclusions can be drawn:

1. The soil modulus obtained from Pressuremeter test is reasonably accurate to be used for modeling the deformation of secant pile induced by excavation. With combination with the Hardening Soil model, the computed wall deflection yielded a close result with the field measurement.
2. The effective soil nailing inclination was 30° where it yielded the smallest deformations induced by excavation
3. The longer length of soil nailing would yield a smaller deformation induced by excavation.

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