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Finite Element Analysis of the Movement of the Tie-Back Wall in Alluvial-Silty Soils

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Abstract

Excavations in urban–developed areas were commonly supported by diaphragm walls with internal braces or tieback anchors. There are still required the necessary civil works to serve the demands and also to solve the environmental problems. Wales and cross-lot struts are by far the predominant method for wall support, the large working space inside the excavation provided by a tieback anchor system has a significant construction advantage. This paper aims to evaluate the soil stiffness parameters of the alluvial Taipei soil for tie-back diaphragm wall based on back analysis of case study. The case histories of the Taipei County Administration Centre (TCAC) and NTU Hospital (NTUH) were studied in this paper. The deformation analysis was carried out by available finite element analysis tool using PLAXIS. In the analysis, beam element method together with an elastic perfect plastic soil model was used to design the diaphragm wall and the tieback anchor system. The soil was modelled as Mohr-Coulomb model. According to the basic design, the clay deposits are modelled as undrained behaviour while silty-sand behaves in drained condition. The simulation results show that the maximum horizontal movement occurred at around the bottom of wall. At the final stage of construction, the root mean square deviation (RSMD) between measured and calculated the wall movement was 4% and 7% respectively at TCAC and NTUH sites. It was concluded that tied-back diaphragm wall can be satisfactorily modelled using elasto-plastic Mohr-Coulomb soil model. The predicted soil's modulus of elasticity can be obtained from the SPT-N relationship, for clay deposit layer and for silty-sand deposit.

Keywords: anchors; diaphragm wall; alluvial soils; lateral-movement; finite element method.

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1. Introduction

Rapid development in urban areas and limited space for construction in cities imposed engineers to apply a suitable and reliable technology and construction method. Wall-supported deep excavation is now the common construction in urban environment. Typically, excavations in those areas are supported by diaphragm walls with internal braces or tieback anchors. There are still required the necessary civil works to serve the demands and also to solve the environmental problems. Wales and cross-lot struts are by far the predominant method for wall support, the large working space inside the excavation provided by a tieback anchor system has a significant construction advantage.

Numerical analyses have been used and are capable of modeling serious phases of excavation such as dewatering, soil removing process, strut installation and preloading. However, the accuracy of the numerical results mainly depends on the choice of an appropriate soil model and the calibration of the soil parameters to the analyses. Unfortunately, the soil parameters from laboratory tests are often not reliable due to sampling disturbance, preparation, and differences in boundary conditions. For this reason, field monitoring is often carried out during construction to observe the performance of the excavation stages. Meanwhile, the measured values can serve as input information of the appropriate optimization analysis to obtain a set of soil parameters such that the calculated deformation closest to the measured values. This process is referred as feedback analysis. Ou and Tang (1994) employed optimization techniques to determine soil parameters for finite element analysis in deep excavation. Chi et al (1999) developed an information construction approach that the optimization algorithm was used to back-analyze soil parameters, and back-analyzed soil parameters were then used to predict the wall deflection of next excavation stage.

The use of field instrumentation results to back-calculate the soil parameters allowing the engineer to account for the global response of a braced excavation system. This paper aims to evaluate the soil stiffness parameters of the alluvial Taipei soil for tie-back diaphragm wall. The selected case history was recorded in Liao and Hsieh (2002). The parameter will be back analyzed by using finite element method (FEM).

2. Projects Description

TCAC building

The Taipei County Administration Center (TCAC) was a 33-story high building with four basement levels. The size of this excavation was 155 m long, 93 m wide and 20 m deep. Figure 1a illustrates the soil profile and the tied-back wall. The subsoil strata were low-plasticity clay (CL) interlayer with silty-sand (SM). To support this excavation, a 1.2 m thick tied-back diaphragm wall with panel depths of 38 m. The total lengths of the tieback anchors were kept to less than 25 m. The groundwater table was 6 m below the ground's surface.
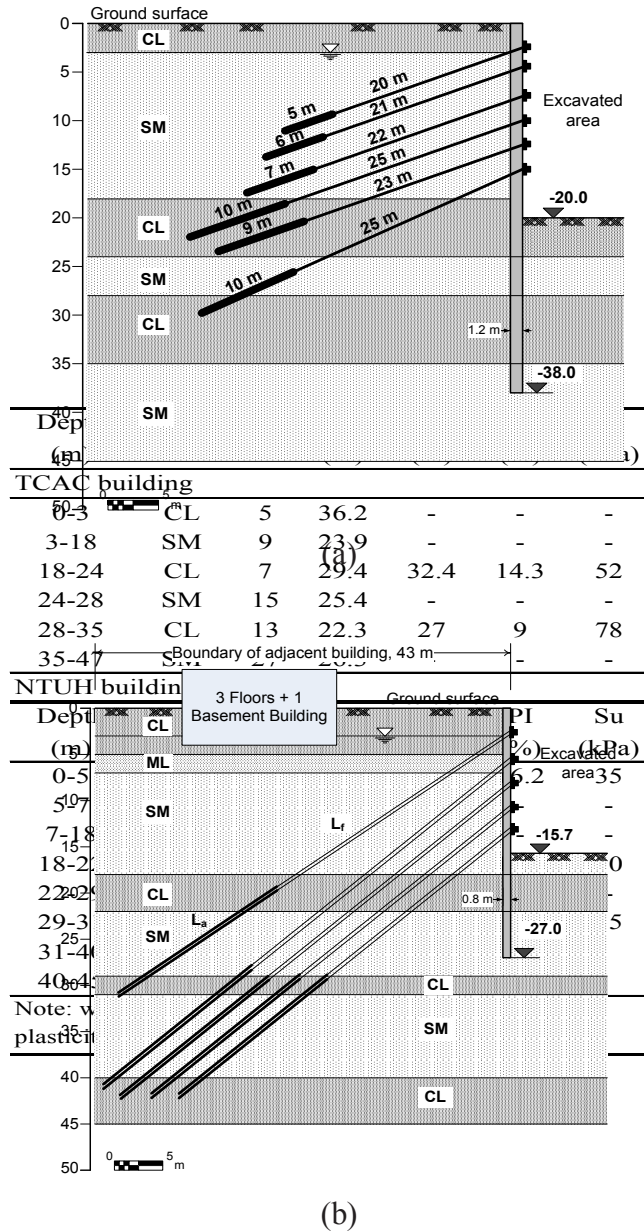
National Taiwan University Hospital

(a)

(b)

Figure 1. Soil profile and tied-back excavation wall of the TCAC site (a) and NTUH site (b)

The National Taiwan University Hospital (NTUH) was a 15-story high building with four levels of basement. The excavation of the basement of NTUH was about 180 m long, 140 m wide, and 15.7 m deep. The diaphragm wall was 0.8 m thick and 27 m deep; the anchor system had five tieback levels anchors (Figure 1b). The design loads of different tieback levels varied from 400 to 600 kN (Table 1). The groundwater table was about 3 m below the ground's surface.

Wall construction sequence and wall deformation

Diaphragm wall and multilevel tieback anchors were used to support the cut and tied-back excavation. The depth of each excavation stage is usually 50–80 cm deeper than the tieback level. The total of construction stage has been done in 8 and 7 stages respective for TCAC and NTUH excavation project. The groundwater table inside the excavation wall became lower with the depth of the excavation, but the groundwater table outside did not lower during excavation of the basement or anchor installation by means dewatering in the excavation area after each excavation stage. The lateral wall movement (Figure 2) was measured after installation of the tieback anchors at each excavation stage and corrected for bottom movement of the inclinometer casing (Liao and Hsieh 2002).

Table 1. Information on Tieback Anchors (Liao and Hsieh 2002)

Taipei County Administration Center (anchor type: cone shape SBMA underreamed anchor)

Anchor Level	Design Load (kN)	Initial Locked-in Load (kN)	Position (m)	Inclination to Horizontal (deg)	Horizontal Spacing (m)	Anchor[b] Diameter (m)	Total Length (m)	Number of Anchorage Bodies	Underreamed Length (m)	Number of Strands ($d=12.7$ mm)	Measured Residual Load (kN)
1st	400	420	−2.5	20	2.12	0.13→0.5	20	3	5	6	320
2nd	600	600	−4.5	20	2.12	0.13→0.5	21	4	6	8	500
3rd	700	710	−7.5	20	2.12	0.13→0.5	22	4	7	8	480
4th	700	600	−10.0	20	2.12	0.13→0.5	25	4	10	8	500
5th	700	630	−12.5	20	1.59	0.13→0.6	13	4	9	8	540
6th	700	650	−15.0	20	1.59	0.13→0.6	23	4	10	8	640
7th	700	620	−16.5	25 (odd) 30 (even)	1.27	0.13→0.6	25	4	10	8	620

[a] Anchor diameter = diameter of drilling casing.

[b] 0.13 m→0.5 m: underreaming gradually from $d=0.13$ to 0.5 m.

National Taiwan University Hospital (anchor type: tension type shaft anchor)

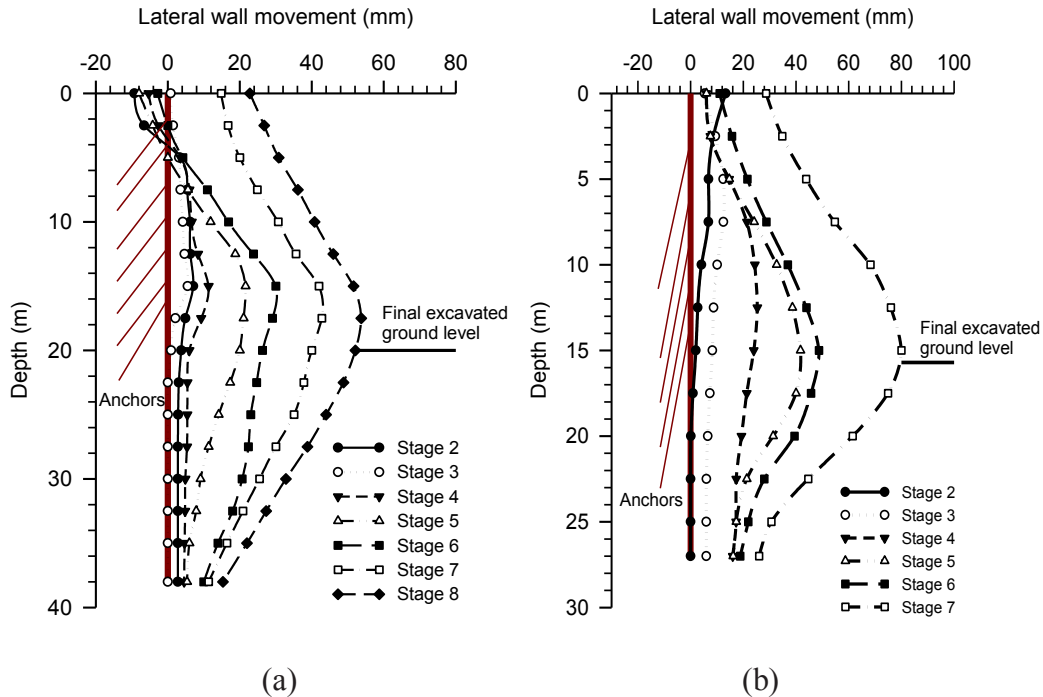| Anchor Level	Design Load (kN)	Initial Locked-in Load (kN)	Position (m)	Inclination to Horizontal (deg)	Horizontal Spacing (m)	Anchor[a] Diameter (m)	Total Length (m)	Free Tendon Length, Lf (m)	Fixed Tendon Length, La (m)	Number of Strands ($d=12.7$ mm)	Measured Residual Load (kN)
1st	400	300	−2.8	35	1.8	0.114	49.5	29.5	20	5	420
2nd	450	450	−5.8	40	2.4	0.114	55	35	20	6	500
3rd	600	570	−8.4	40	1.9	0.114	52.6	32.6	20	6	560
4th	550	520	−11.0	40	1.6	0.114	48.5	28.5	20	6	510
5th	550	550	−13.4	40	1.9	0.114	44.8	24.8	20	6	580

Figure 2. Profiles of lateral wall movement of tied-back excavation sites (a) TCAC, (b) NTUH

3. Numerical Simulation

3.1. Model and Soil Parameters Used

To simulate the case study, a finite element based computer program PLAXIS 8.x was used in this study. The soil was modeled as *Mohr-Coulomb model* while the *elastic perfectly-plastic* was chosen to model for design the diaphragm wall and the anchor (Liao and Hsieh 2002; Vermer and Brinkgreeve 2002). According to the basic design, the clay deposits are modeled as undrained behavior while silty-sand behaves in a drained condition. The diaphragm wall was modeled as beam element. The thickness of the wall was 1.2 m. The free length of tie-back anchors were simulated as "node to node" spring while the fixed underreamed length was simulated as slender object with axial stiffness (EA) that only sustained tensile strength. The axial stiffness of the anchors were set to 1.1×10^8 kN/m and 1.63×10^8 kN/m for free length and undereamed respectively. Since the diaphragm wall is assumed as impermeable materials, so, in PLAXIS, the soil interface is modeled as *impermeable*. A beam element method together with an elastic perfect plastic soil model was used to design the diaphragm wall and the tieback anchor system. Some of the soil parameter and anchor parameter are provided in Table 1.

The strength parameter such as Modulus of Elasticity, cohesion and friction angle of soil are back-analysed based on the filed monitoring of the wall movement as Figure 2. For this purpose, the modulus of elasticity can be predicted from the relationship as written in Equation (1) to (4). For saturated clay, the modulus of elasticity can be estimated from the undrained shear strength as follow:

$$\frac{E_u}{S_u} = 500 \sim 800 \tag{1}$$

where, E_u is undrained modulus of elasticity and S_u is undrained shear strength.

For silty sandy, the soil stiffness is estimated based on the shear wave velocity and SPT–N correlation.

$$V_s = 65.58 \left(N \right)^{0.502} \tag{2}$$

$$G = \rho V_s^2 \tag{3}$$

$$E_s = 2\beta G \left(1 + v \right) \tag{4}$$

where,

E_s = Young's modulus of elasticity (MPa),

V_s = shear wave velocity (m/s),

N = SPT-N value,

G = bulk modulus,

ρ = soil density (kg/m^3),

v = poisson's ratio (0.3 ~ 0.35),

β = coefficient = 0.3 ~ 0.5.

The friction angle for silty sand is given in Equation (5) as proposed by Ohsaki which were quoted by McGregor and Duncan (1998).

$$\phi' = (20N)^{0.5} + 15 \tag{5}$$

where ϕ' is effective internal friction angle of soil.

Table 2 and 3 presents input parameters of soil properties and diaphragm wall for back-analysis.

Table 2. Input parameters of soil properties for back-analysis

Taipei County Administration Center

Layer	Soil	Model	Type	γ_d (kN/m³)	γ (kN/m³)	ν	E (kN/m²)	c (kN/m²)	ϕ (°)	Interface
1	CL	MC	Undrained	13.64	18.58	0.49	22750	45.5	0	Impermeable
2	SM	MC	Drained	16.026	19.856	0.3	60476	0	28.4	Impermeable
3	CL	MC	Undrained	15.066	19.495	0.49	26000	52	0	Impermeable
4	SM	MC	Drained	15.643	19.6161	0.3	99780	0	32.3	Impermeable
5	CL	MC	Undrained	16.909	20.68	0.49	39000	78	0	Impermeable
6	SM	MC	Drained	15.422	19.477	0.3	178751	0	38.2	Impermeable

National Taiwan University Hospital

Layer	Soil	Model	Type	γ_d (kN/m³)	γ (kN/m³)	ν	E (kN/m²)	c (kN/m²)	ϕ (°)	Interface
1	CL	MC	Undrained	13	18.2	0.35	17500	35	0	Impermeable
2	ML	MC	Drained	16	20.432	0.3	3024	0	22.7	Impermeable
3	SM	MC	Drained	14	18.452	0.3	4468	0	27.6	Impermeable
4	CL	MC	Undrained	16	20.96	0.35	35000	70	32.3	Impermeable
5	SM	MC	Undrained	15	18.69	0.3	6205		32.3	Impermeable
6	CL	MC	Undrained	17	21.182	0.35	42500	85	0	Impermeable
7	SM	MC	Drained	15	17.43	0.3	7478		37.4	Impermeable
8	CL	MC	Undrained	14	17.346	0.35	42500	85	0	Impermeable

Table 3. Input parameters of the diaphragm wall

Sites	Type	EA (kN/m)	EI (kNm²/m)	d (m)	w (kN/m/m)	ν	M_p (kNm/m)	N_p (kN/m)
TCAC	Elasto-Plastic	4.2×10^7	5.04×10^6	1.2	28.8	0.15	1.08×10^8	3.12×10^8
NTUH	Elasto-Plastic	2.059×10^7	1.098×10^6	0.8	28.8	0.15	1.08×10^8	3.12×10^8

4. Results and Discussion

4.1. Lateral wall movement

The back-analysed results presented in this paper was relative lateral displacement of the walls due to excavation. In the back analysis, the soil stiffness which has considerable effect on the wall movement has been change by several iteration until the results closed to the measurement in the field. The parameter used in Tabel 2 to 3 were the final iteration which the simulation results was closer to the measured wall movement. The lateral movement of wall from finite element method PLAXIS analysis is shown in Figure 3 and 4 respectively for TCAC and NTUH sites.

It is observed that the maximum horizontal movement occurred at around the bottom of each excavation stage. General speaking, the FEM results match the measured profile well for all stages of excavation except for slight over-estimated of the wall top displacement. In view of good match between the measured and back-analyses wall relative lateral displacement profile, it is evident that the alluvial Taipei soils can be properly modeled using the Mohr-Coulomb model for the tie-back deep excavation

problem. The mismatch results can be explained that in the finite element analysis, the deformation of each nodal (nodal displacement at a point, [**q**]) is formulated as Equation (6).

$$[\mathbf{q}] = [\mathbf{K}] [\mathbf{P}]$$

(6)

where the stiffness matrix, [**K**], is a function of E_s and v. Therefore, determination of both parameters will affect in the deformation analysis (Das 1997). Larger E_s used will result in smaller deformation — the [**K**] matrix is higher; the soil tends to have higher stiffness. Mair (1993) stated that the most important soil parameter is the stiffness of each soil layer, which is normally specified in terms of Young's modulus (E_s). The E_s value is very important especially for the soft clay layer that led to induce the lateral wall movement and ground settlement during excavation works. Secondly, the deviation of result may be generated from lack of information of the soil parameter involved properties of the diaphragm wall, and tied-back anchor. Some of assumption of data used as input parameters are not representative of the real behavior. However, some soil parameter suppose to be closer to the real properties e.g. unit weight, since those are derived from the relevance data such as in situ water content.

In the problem analyzed, the lateral movement at the top and the bottom of the wall is closer to the measured movement at the final stage as shown in Figure 3 and 4. However, the movement at the top of excavation is not closer to the measurement. It is probably caused by the stiffness of the diaphragm wall and the properties of the anchors. Since the wall and anchor are modeled as elastic perfectly plastic, it need a yield stress data and maximum force (for anchor) data. It was observed from the figures that diffulties were faced to model the diaphragm wall behavior at the initial stage of excavation and tied-back installation. Vaziri (1996) studied that behavior was arised due to the soil behave linearly elastically, as long as the pressures correspond to stress levels lying between the limits. Where the lateral movement of the wall correspond to a pressure outside of the allowable limits.

To evaluate the numerical model, *root mean square deviation* (*RSMD*) was calcluated between the maximum measured and calculated lateral movement of the wall at each stages. The *RSMD* is calculted using Equation (7), as following:

$$RSMD\left(\Theta_1, \Theta_2\right) = \sqrt{\frac{\sum_{i=1}^{N}\left(\theta_{1,i} - \theta_{2,i}\right)^2}{N}}$$

(7)

where, Θ_1 and Θ_2 are measured and calculated wall movement at particular depth ($\Theta_1 = \{\theta_{1,1}; \theta_{1,2}; \ldots\}$, $\Theta_2 = \{\theta_{2,1}; \theta_{2,2}; \ldots\}$).

Table 4 presents the *RSMD* of the lateral movement for both TCAC and NTUH sites. The calculation of *RSMD* in Table 4 indicates that the deviation between the measured and numerical simulation is smaller for final stage of excavation. The deviation of lateral wall movement for TCAC site varies from 2.4 mm to 5.10 mm, whilst the deviation is 5.89 mm to 7.33 mm for NTUH site. If the *RSMD* of the lateral movement is compared to the maximum wall movement at each stages, it is observed that the deviation is larger at initial stages for both studied sites. This behavior was also observed by Phienwej and Gan (2003). Burland (1989) stated this condition due to unloading-stress effect and non-linear stress-strain behavior of soils. A small strain modulus value of soils should be adopted in the linear elasto-plastic continuum finite element analysis.

Table 4. The *RSMD* of the lateral wall movement

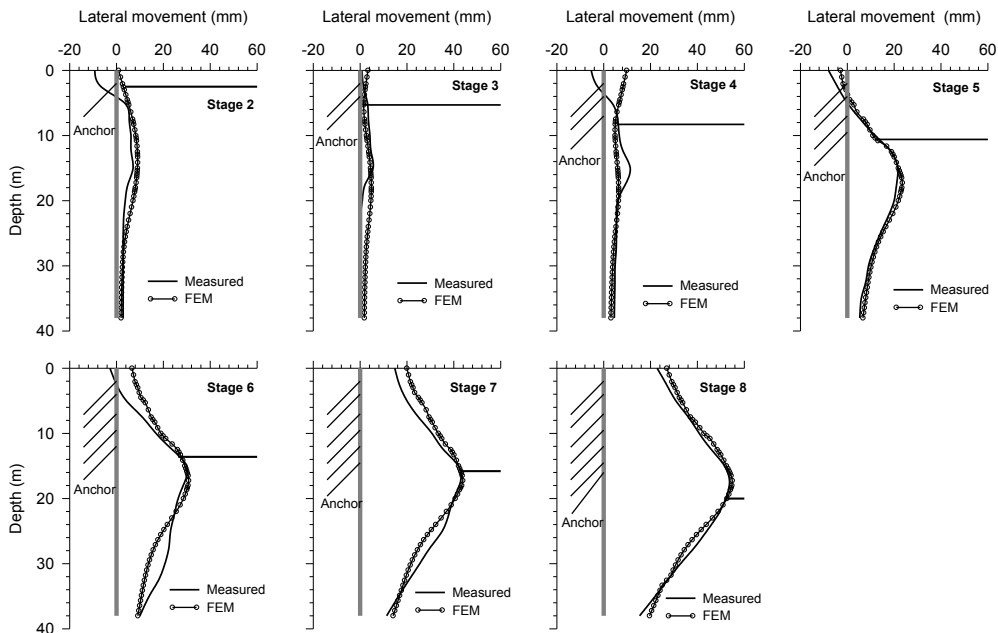| Construction Stages	*RSMD* (Θ_1, Θ_2) mm		Ratio to maximum lateral wall movement	
	TCAC site	NTUH site	TCAC site	NTUH site
2	3.93	6.47	56%	48%
3	2.35	6.43	42%	52%
4	5.10	3.85	45%	15%
5	2.00	6.93	9%	17%
6	5.00	7.33	17%	15%
7	3.59	5.89	8%	7%
8	2.40		4%	

Figure 3. Comparison of the lateral movement of tied-back wall between field measurement and FEM for TCAC building
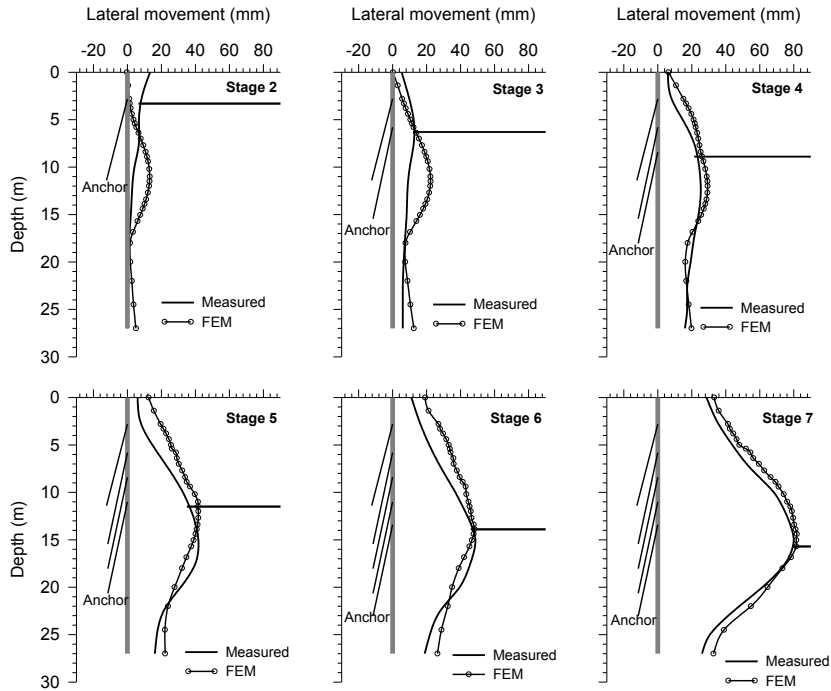
Figure 4. Comparison of the lateral movement of tied-back wall between field measurement and FEM for NTUH building
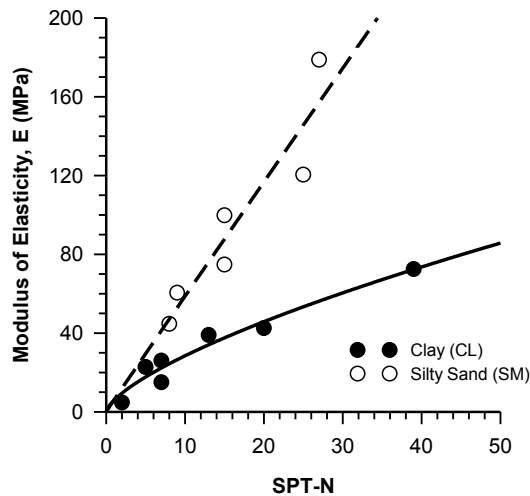

Figure 5. Correlation between E_s and SPT-N for alluvial soil in Taipei

4.2. Correlations between E_s and SPT-N

The standard penetration tests (SPT) commonly carried out at site were correlated to obtain strength and stiffness parameters of the alluvial soils for design because it is economic and easily available. Usually the correlation was based on the contention that the SPT-N values, which were obtained extensively at site. From the FEM back-analysis, the estimated Young's modulus of elasticity (E_s) varied with the SPT-N value.

Hence, the correllation is shown in Figure 5. For practical prupoes, the suggested correlations between SPT-N values and the Young's Modulus of elasticity (E_s) used in the "Mohr-Coulomb" model are written in Equation 8a and 8b.

For clay layer:

$$E_s = 5.878N^{0.685} \tag{8a}$$

For silty sand layer:

$$E_s = 5.959N^{0.993} \tag{8b}$$

where, N is SPT value, and the unit of Young's modulus of elasticity (E_s) is in MPa.

5. Conclusions

In conclusion, the displacement patterns of the walls and ground surface settlement profile obtained from the FEM back-analyses agree reasonably well with the measured values. Therefore, it is evident that alluvial soils in Taipei can be properly modeled using the "Mohr-Coulomb" model for the deep excavation problem. For the practical purposes, the Young's modulus of elasticity (E_s) of the alluvial soil in Taipei can be predicted from SPT-N values, which is $E_s = 5.878N^{0.685}$ for clay and $E_s = 5.959N^{0.993}$ for silty-sand deposit. The simulation results show that the maximum horizontal movement occurred at around the bottom of wall. At the final stage of construction, the root mean square deviation (*RSMD*) between measured and calculated the wall movement was 4% and 7% respectively at TCAC and NTUH sites

Acknowledgement

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