EFFECT OF SOILCRETE CHARACTERISTICS ON SURFACE SETTLEMENT DURING TUNNELING IN VIETNAM

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Abstract: Excess surface settlement during construction of underground structures such as tunnels is concerned for historic buildings in big cities. A metro line No. 1 located at 20 m deep under the ground surface will be built in Ho Chi Minh City (HCMC) soon, and this metro crosses the City underneath many historic buildings. Reinforcing the soil mass surrounding the tunnel by soil-cement mixing (soilcrete) using jet grouting is considered a feasible solution to reduce surface settlement. However, appropriate characteristics of soilcrete for the HCMC's geological conditions have not been thoroughly investigated. This study investigated the relationship between the characteristics of soilcrete (young modulus and thickness) and surface settlement at the city opera house, the historic building close to the metro, with a maximum allowable surface settlement of 10 mm.

Keywords: *surface settlement; Jet grouting; soilcrete; TBM; tunnel; soil reinforcement, ground improvement.*

1.0 Introduction

Transportation system in the big cities in Vietnam such as Ho Chi Minh City (HCMC) and Hanoi has become overloaded, and available urban land for expansion of the transportation system becomes limited. Therefore, underground transportation system is considered a promising solution. However, construction of underground structures like metro in big cities with high population and condensed buildings may affect existing structures on the ground surface. Recently, HCMC People's Committee has approved a primary design of the Metro line No. 1 from Ben Thanh to Suoi Tien with total length of 19.7 km including 2.6 km underground across the city. This underground section will be constructed using a Tunnel Boring Machine (TBM) (Urban Railroad Management Board – URMB 2010). Underground construction using the TBM may cause surface settlement around a construction site (Maidl 1996). The 2.6-km underground section of the metro crosses through beneath almost all important buildings in the downtown HCMC, and the metro goes underneath and close the Opera House, a historic building, that a maximum surface settlement should be less than 10 mm (Fig. 1, 2). Thus, soil

reinforcement or improvement needs to be done before the Metro constructed using a TBM to mitigate surface settlement for this building.

Jet Grouting is a soil improvement using high pressure air, water, or cement slurry (1 – 40 MPa) to erode in-situ soil and mix in-place the soil with cement slurry to create soil cement columns (soilcrete) which have higher strength than that of the in-situ soil (Burke 2004). Jet Grouting technology is proposed to reinforce the sub-soil before the Metro construction using the TBM to protect the Opera House (URMB 2010). Jet Grouting technology was first developed in Japan in 1970s and widely applied in Europe and United State in 1980s (Essler & Yoshida 2004). Jet Grouting can be implemented at small areas and maintains intact surface without excavation. Therefore, Jet Grouting can be used to reinforce the sub-soil to mitigate surface settlement effectively at limited area sites in big cities such as HCMC. However, research on Jet Grouting technology applied to lessen surface settlement during underground construction is limited for HCMC geological conditions, even though Jet Grouting technology has been utilized to construct cut-off walls for seepage mitigation in water resources' structures in Vietnam from 2004 (Nguyen Quoc Dung et al. 2010) and evaluated the potential application in Vietnam (Tran-Nguyen 2011, Ly Huu Thang & Tran Nguyen Hoang Hung 2012, Tran-Nguyen et al. 2012). This paper focuses on the characteristics of soilcrete created by Jet Grouting to mitigate surface settlement for the Opera House during construction of the Metro No. 1 in the HCMC.

2.0 Site Conditions

2.1 Description of the Metro No. 1

A Metro line No. 1, Ben Thanh – Suoi Tien, was approved by HCMC People's Committee funded by the Official Development Assistance (ODA). The total length of the Metro is 19.7 km including 17.1 km above surface and 2.6 km underground (Fig. 1). The underground section passes many important buildings in the downtown of the HCMC (Fig. 2).

The two typical cross-sections of the Metro Line No. 1 used along the underground longitudinal profile of the Metro in the downtown of HCMC are shown in Figure 3. A 2-vertical tunnel cross-section causes higher surface settlement than a 2-parallel-tunnel cross-section (Mair 1996). Therefore, a 2-vertical tunnel cross-section will be used for this investigation. Table 1 shows key parameters of the Metro and the TBM at the study section.

Table 1 : Key Parameters of The Cross-Section At The Opera House And That of A TBM (URMB 2010)

	Unit	**Value**
Inside diameter	m	6.05
Outside diameter	m	6.65
Diameter of the TBM	m	6.79
Length of the TBM	m	7.8

Figure 1 : The 19.7-km Metro line No. 1 from the downtown to the east side of HCMC.

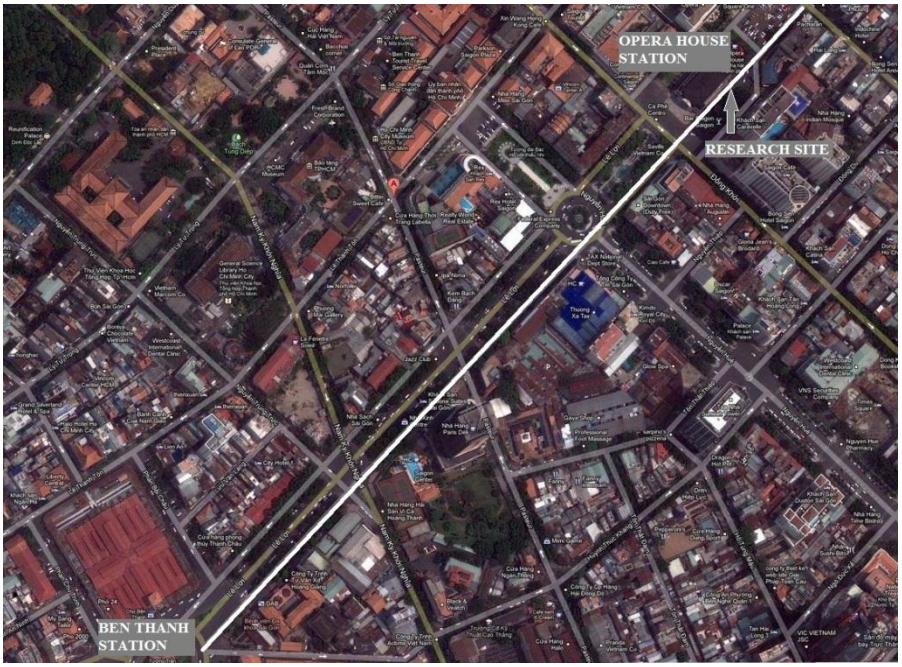


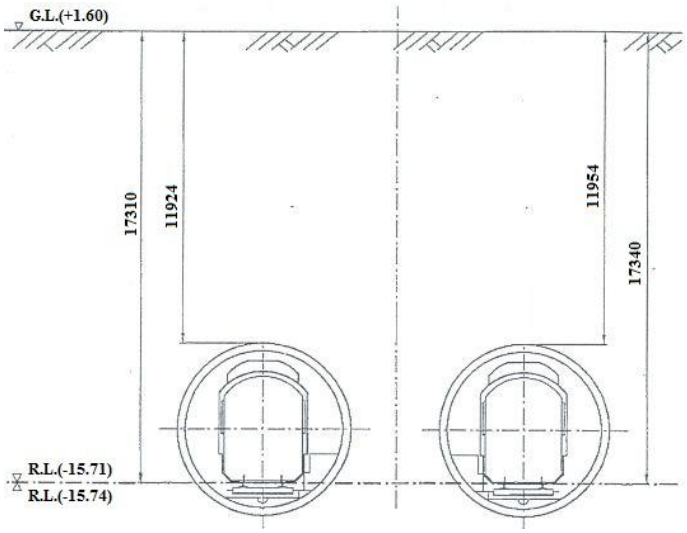
Figure 2 : Plain view of the Metro No. 1 in the HCMC downtown (Google maps)

2.2 *Geological properties*

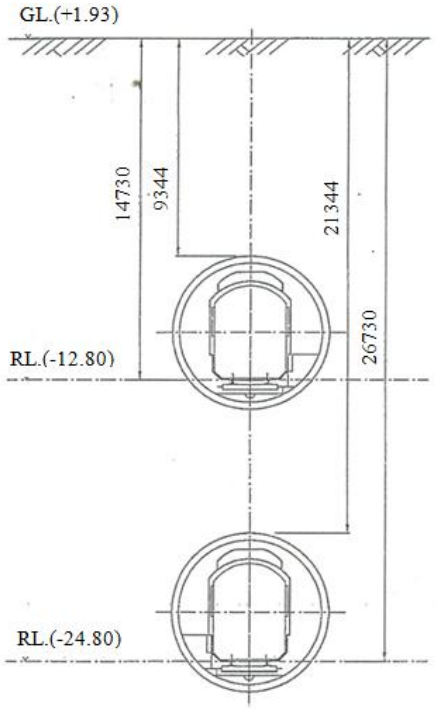
Soil properties at the study site are given in Table 2. In general, geological conditions are good and no soft deposit layers in the soil profile.

Table 2 : Soil Properties at The Study Site (URMB 2010)

Layers	**Thickness** m	γ_{Sat} kN/m^3	c kN/m^2	ϕ Deg.
Surface soil	0.5	17	12	-
Clay	2.2	17.8	12	-
Fine sand	11.3	20.2	-	26
Medium sand	9	20.4	-	31
Fine sand	10.5	20.1	-	33
Medium sand	> 2	19.4	-	34



(a) 2-parallel tunnel cross-section



(b) 2-vertical tunnel cross-section

Figure 3 : Two typical tunnel cross-sections applied in the metro line No. 1 (URMB 2010)

3.0 Methodology

3.1 Background

Based on the Gauss curve, Peck (1969) proposed a concave shape for surface settlement above tunnel (Nguyen Duc Toan 2006). Nguyen Duc Toan (2006) proposed some empirical equations for surface settlement analysis such Herzog (1985), O'Reilly & New (1982), and Maidl (1996).

Alternatively, the FEM can be utilized to analyze surface settlement for the subsoil either reinforced or not. The FEM (the PLAXIS 2D v.8.5 software) was also used to investigate surface settlement varying with the characteristics of soilcrete (young modulus, E, and thickness, δ) created to reinforce the soil mass surrounding the Metro before tunneling. This investigation neglected surface loads for numerical simulations to compare the three methods: O'Reilly & New (1982), Herzog (1985), and FEM because the equation of O'Reilly & New (1982) ignores surface loads.

3.2 Methods

3.2.1 Empirical equations

Surface settlement is assumed to approximate to the Gauss curve (Nguyen Duc Toan 2006) as shown in Equation (1)

$$S = S_{\max}.\exp\left(\frac{-y^2}{2.i^2}\right) \tag{1}$$

where S -surface settlement, Smax -maximum surface settlement, y - distance from the centerline of a tunnel, i - distance from the centerline of a tunnel to the inflection point in the Gauss curve.

A maximum surface settlement can be determined using Herzog (1985)'s Equation (2) (Nguyen Duc Toan 2006):

$$S_{\max} = 0.785(\gamma Z_O + P_S)\left(\frac{D^2}{iE}\right) \tag{2}$$

or O'Reilly & New (1982)'s Equation (3) (Nguyen Duc Toan 2006):

$$S_{max} = \frac{0.313 V_L D^2}{i} \quad (3)$$

where γ - average unit weight of all soil layers (kN/m^3); Z_o - depth of a tunnel from its centerline to the ground surface (m), P_s - surcharge (kN/m), D - outside diameter of a tunnel (m), E - young modulus of the soil mass surrounding (kN/m^2), V_L - volume of the soil mass lost per 1 m long (%). i can be determined using Equation (4)

$$i = K.z_o \quad (4)$$

where K - dimensionless empirical constant depending on soil type (i.e., K = 04-0.5 for cohesive soils, 0.25-0.35 for granular soils, 0.7 for soft and silty clay), z_0 – the depth of the tunnel axis below the ground.

In the case of multiple soil layers, K_{eq} is used instead of K and can be computed using Equation (5) and (6)

For $z_0 < 1.5D$,

$$k_{eq} = \frac{z_1 k_1 + ... + z_n k_n}{z_{tot}} \quad (5)$$

For $z_0 > 1.5D$,

$$k_{eq} = \frac{0.35(z_1 k_1 + ... + z_m k_m) + 0.65(z_{m+1} k_{m+1} + ... + z_n k_n)}{0.35(z_1 + ... + z_m) + 0.65(z_{m+1} + ... + z_n)} \quad (6)$$

where K_{eq} - the average value of various value of k_i, k_i - dimensionless empirical constant of each soil layers above the tunnel, z_i – the thickness of each soil layers above the tunnel.

For the Herzog (1985)'s Equation, i is determined using (7):

$$i = \frac{i_1 + i_2 + i_3 + i_4}{4} \quad (7)$$

where i_1 - Glossop (1978)'s Equation (8), i_2 - O'Reilly & New (1982)'s Equation (9), i_3 - Schmidt (1969)'s Equation (10), i_4 - Arioglu (1992)'s Equation (11), respectively (from

Ercelebi et al. 2011), z_0 - the depth of the tunnel axis below the ground, R – Radius of the tunnel

$$i_1 = 0.5z_o \tag{8}$$

$$i_2 = 0.43z_o + 1.1 \tag{9}$$

$$i_3 = R\left(\frac{z_o}{2R}\right)^{0.8} \tag{10}$$

$$i_4 = 0.9R\left(\frac{z_o}{2R}\right)^{0.88} \tag{11}$$

3.2.2 FEM

Once the Metro No. 1 is constructed using a TBM and installing tunnel linings behind it, a gap between the tunnel lining and the soil mass surrounding due to excavation of the TBM causes deformation and stress re-distribution. This gap creates contraction or shrinkage because of volume loss, V_L. The volume loss generates deformation of the soil surface (e.g., surface settlement) which may damage existing structures such as buildings. The volume loss, V_L, can be defined by Equation (4) (modified from Brinkgreve 2002).

$$V_L = \frac{\textit{Original tunnel area} \text{ minus } \textit{Area at current step}}{\textit{original area of tunnel}} \times 100\% \tag{12}$$

Surface settlement depends on V_L values, and V_L varies from 0.3% to 5.0% depending on soil types (Nguyen Duc Toan 2006). This study used V_L of 1.8% and 3.5% to analyze surface settlement to compare with analysis using the empirical equations.

Effects of the volume loss to surface settlement can be simulated using the FEM (the Plaxis 2D v.8.5 software) via the contraction method. In the Plaxis 2D software, a contraction can be activated via the staged construction mode and input volume loss value in percentage. This study analyzed surface settlement during the Metro No. 1 constructed in the HCMC at the Opera House based on variation of V_L. The Mohr–Coulomb model was applied to simulate soil behavior. A typical FEM mesh using the Plaxis software to simulate the typical cross-section is shown in Figure 3.

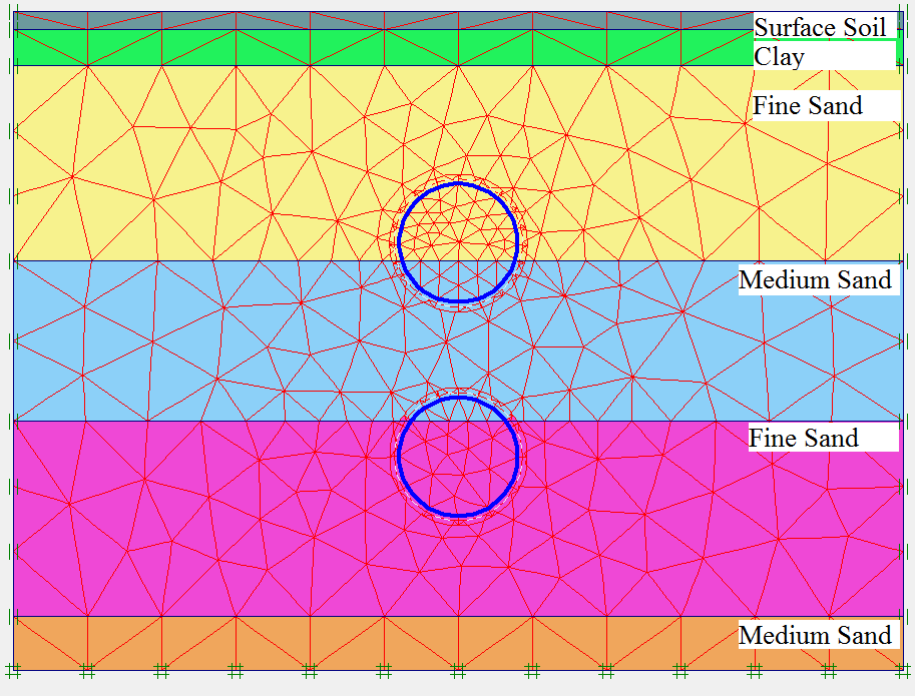


Figure 4 : FEM mesh in simulations of the typical cross-section of the Metro No. 1 using PLAXIS 2D v8.5 software.

4.0 Analysis and Results

This study analyzed surface settlement in three cases by several simulations using the both empirical equations and FEM.

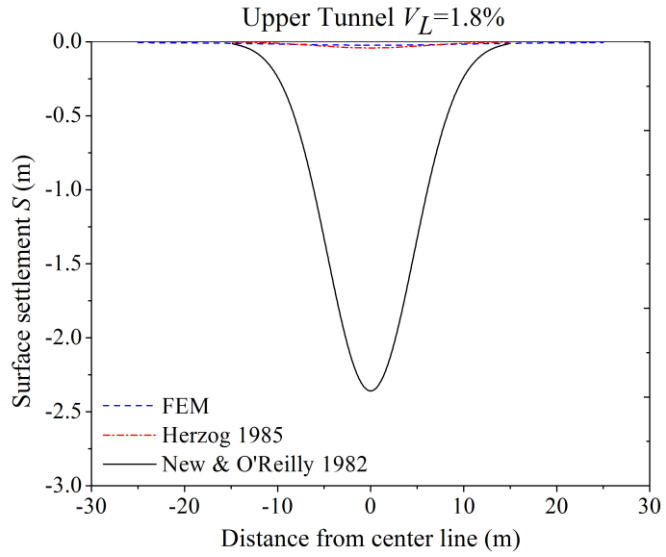
(1) Sub-soil without reinforcement for the individual tunnels.

(2) Sub-soil reinforced by soilcrete using Jet Grouting with the upper tunnel tunneled first and then the lower tunnel.

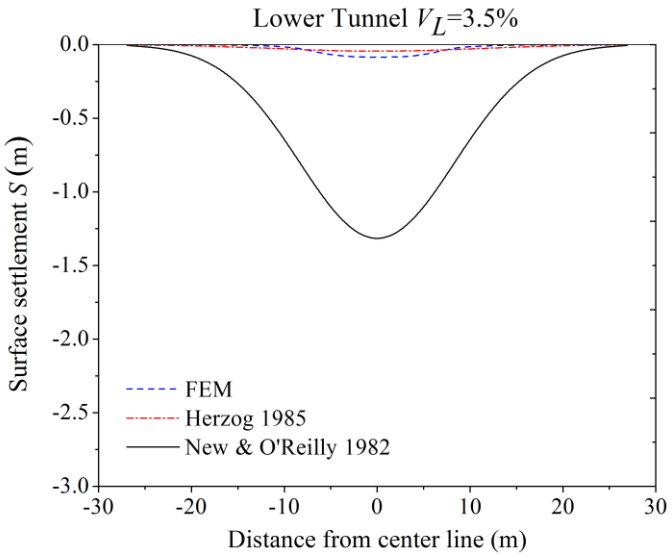
(3) Investigation of relationship of surface settlement and the characteristics of soilcrete.

4.1 Surface settlement analysis in case of the sub-soil without reinforcement

Surface settlement was analyzed using the empirical equations such as Herzog (1985) and O'Reilly & New (1982) (referred from Nguyen Duc Toan 2006), and the FEM. The result is shown in Figure 4.



(a) Upper tunnel's settlement, V_L = 1.8%



(b) Lower tunnel's settlement, V_L = 3.5%

Figure 5: Surface settlement analysis for the study cross-section

The results show that surface settlement during tunneling the upper tunnel is larger than that of the lower tunnel for all methods (Fig. 4). The surface settlement generated due to construction of the lower tunnel is less than that of the upper tunnel. It also can be seen that the simulations using the FEM and Herzog 's Equation are almost identical, but not for O'Reilly & New 's Equation.

4.2 Surface settlement analysis with the sub-soil reinforced using Jet Grouting

In the primary design, a rectangular frame reinforcement by Jet Grouting was created before tunneling the Metro (Fig. 5). Soilcrete properties used for the simulations are given in Table 3 based on Almer (2001) and Bzowka (2004). Three cases were investigated in this analysis: (1) δ = 1 m and observe variation of surface settlement in Young modulus, E; (2) E = 500 MPa and examine variation of surface settlement in soilcrete wall thickness, δ; (3) variation of surface settlement with changing of δ from 0.4 – 3.5 m, and E from 100 – 5000 MPa.

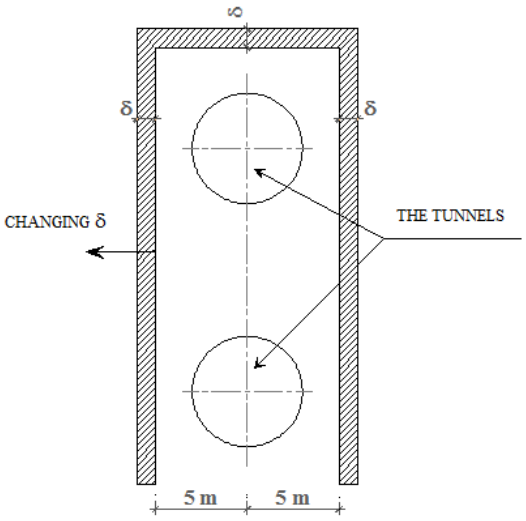


Figure 6 : The sub-soil reinforced by Jet Grouting at the cross-section at the Opera House (URMB 2010)

Table 3 : Soilcrete properties used for FEM simulations (Almer 2001, Bzowka 2004)

	Symbol	**Unit**	**Value**
Thickness,	δ	m	change
Unsaturated Density	γ_{Unsat}	KN/m^3	20
Saturated Density	γ_{Sat}	KN/m^3	22
Young modulus	E_{ref}	KN/m^2	change
Poison ratio	v		0.2
Cohesion	c	KN/m^2	100
Friction angle	φ	degree	30
Dilation angle	ψ	degree	0
Horizontal permeability	K_x	m/day	0.5
Vertical permeability	K_y	m/day	0.5

Value of V_L, in general, should be appropriately decided for surface settlement analysis depending on soil types. Nguyen Duc Toan (2006) recommends that V_L can be selected in a range of 0.3% to 0.8% for sand. This study used V_L = 0.5% for the investigated cross-section due to mainly sand soil along the soil profile.

The result of case #1 shows in Figure 6 with δ = 1 m fixed. Case #2 with E = 500 MPa fixed is plotted in Figure 7. Figure 8 displays the result of case #3, variation of surface settlement in changing the characteristics of soilcrete (E and δ).

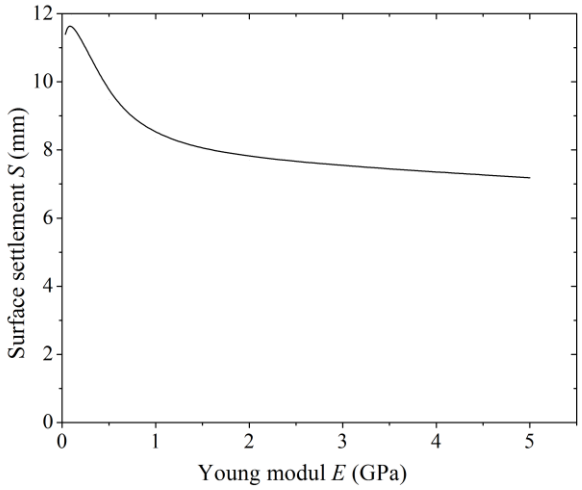


Figure 7 : Relationship of surface settlement and E at δ = 1 m

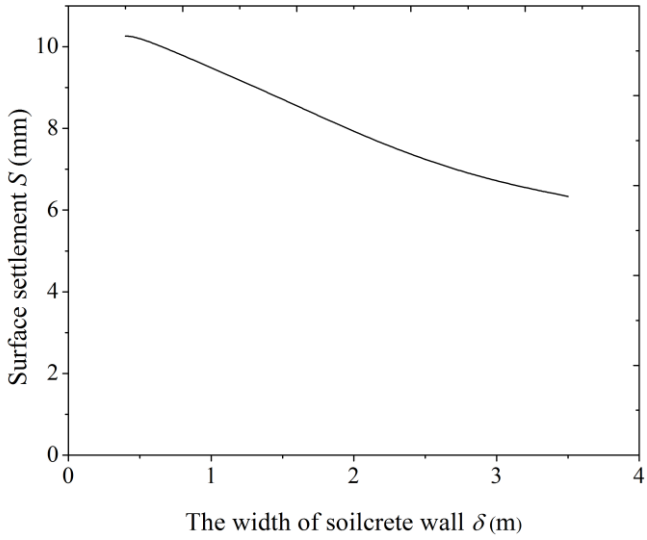


Figure 8 : Relationship of surface settlement and δ at E = 500 MPa

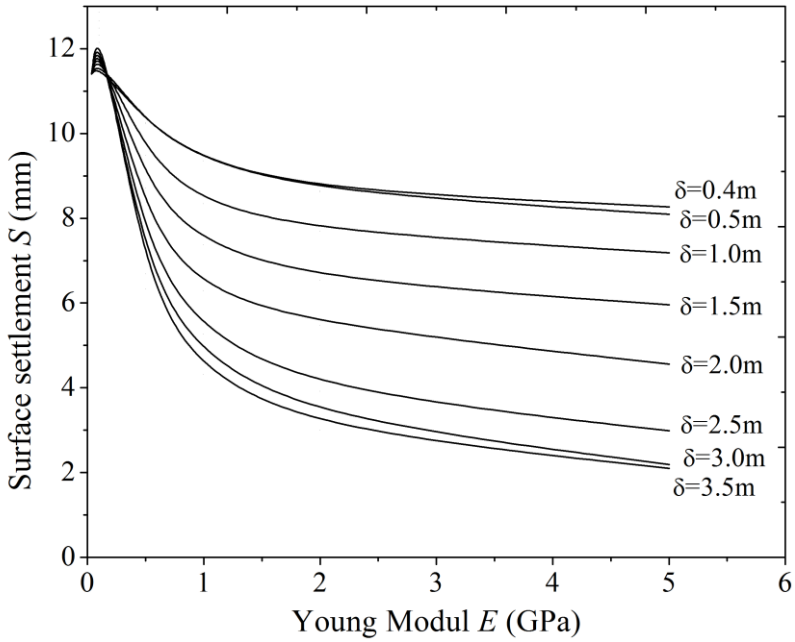


Figure 9 : Relationship of surface settlement and the characteristics of soilcrete (E & δ)

5.0 Discussion

Surface settlement simulated using the O'Reilly & New (1982)'s Equation provided an impractical result to compare with the Herzog (1985)'s Equation and the FEM since the O'Reilly & New (1982)'s Equation doesn't take the stiffness of the sub-soil into account. The surface settlement analyzed using the Herzog (1985)'s Equation and the FEM agrees well with Nguyen Duc Toan (2006) study.

The pilot studies shown in Figure 6 & 7 indicate that surface settlement is sensitive to Young modulus of soilcrete, *E*, when *E* is smaller than 1 GPa, and the surface settlement decreases slightly when *E* is larger than 1 GPa (Fig. 6). The surface settlement decreases fairly with increasing the thickness of soilcrete (Fig. 7). This result recommends that increase of soilcrete thickness is least effective at $E <= 1$ GPa. Figure 8 is resulted from the FEM simulations for the geological conditions of the HCMC. This plot provides a guideline for designers to determine the characteristics of soilcrete quickly to meet a required surface settlement for primary design in the HCMC geology.

Tan & Ranjith (2003) proposed using steel pipes to reinforce the subsoil in a rectangular form surrounding a tunnel. A surface settlement reduced about 50% for a 0.5-m rectangular form using steel pipes having the Young modulus of 70 GPa and the yield strength of 320 MPa. This study suggested a reinforced structure having an approximate stiffness with that of Tan & Ranjith (2003) using a 2.5-m rectangular soil cement mixing (soilcrete) wall created by a Jet Grouting technique. A surface settlement decreases up to 40% for a soilcrete young modulus of 5 GPa.

6.0 Conclusions

This study investigated the characteristics of soilcrete created by Jet Grouting to mitigate surface settlement during constructing the Metro line No. 1 in the HCMC. The section at the Opera House was chosen for this investigation. The both empirical equations and FEM were utilized to analyze surface settlement. The surface settlement obtained from The Herzog's Equation agrees well with that of the FEM. The findings suggest that the FEM is a power tool for surface settlement analysis.

The investigation of the characteristics of soilcrete on surface settlement for the geological properties of the HCMC provides the following conclusions:

(1) Increase of the Young modulus of soilcrete, *E*, is more effective than increase of soilcrete thickness when *E* is less than 1 GPa.

(2) Increasing in thickness of a soilcrete wall reduces surface settlement significantly when *E* is greater than 1 GPa.

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