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Adopting Numerical Models for Prediction of Ground Movements Induced by Deep Excavation

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***Abstract:** Control of ground surface settlement induced by deep excavation is of major concern in order to attain safety of adjacent structures and utilities against excessive or differential settlements. Accurate prediction of ground surface movements is an important design criterion in the analysis and design of excavation supporting systems. Many codes of practice are based on a design criterion that satisfies a factor of safety preventing collapse of the system and its surrounding soil.*

In this research, finite element modeling is adopted to numerically simulate the performance of deep excavation systems and the associated ground movements. The soil behavior was simulated using two types of models; the Mohr-Coulomb model (MC) and the Hardening Soil Model (HS). Field data from monitoring a real deep excavation case history of a retaining system was considered to check the validity of the proposed numerical modeling. A simpler equivalent section replacing the multi-layered soil profile was verified. Then, a sensitivity study has been conducted to study the influence of major parameters that affect ground movements induced by deep excavation. The results of the parametric study were accomplished to construct design charts and drive empirical equations by implementing a design parameter, called the "Stiffness Ratio (R)", that represents the supporting system stiffness. From these suggested charts and equations, the percentage of maximum vertical ground movements to wall height can be estimated.

***Keywords:** Deep excavation, Stiffness ratio, Ground movements, Side support system.*

I. INTRODUCTION

Underground construction has become a common practice worldwide because of the space limitations in urban areas. Control of ground surface settlement induced by deep excavation is of major concern in order to attain safety of adjacent structures and utilities against excessive or differential settlements. Deformations of excavation support system, lateral wall movements and ground surface settlements are influenced by several factors including methods of support system installation, soil conditions, safety factor against basal heave, and support system stiffness. The stiffness of an excavation support system is a function of the flexural rigidity of the wall element, the vertical and horizontal spacing of its supports (struts or anchors), the structural stiffness of the support elements and the type of connections between the wall and its supports, [1].

Consequently, accurate prediction of ground surface movements is an important design criterion in the analysis and design of excavation supporting systems, [2], [3]. Many codes of practice are based on a design criterion that satisfies a factor of safety preventing collapse of the system and its surrounding soil, [4]. So, this research is conducted to study the ground movements adjacent to deep excavation by integrating field observations and the results of the finite element models. Since majority of the existing empirical design diagrams are mainly based on field measurements and mathematical models, [5] & [6], the main aim of this work is to suggest empirical design charts that deal with different soil types and variable wall configurations and can be used to predict maximum surface deformations.

II. NUMERICAL MODEL

A. Description of the Case Study

In this study, finite element modeling is chosen to numerically simulate the performance of deep excavation systems and the associated ground movements. Field measurements data from a real deep excavation case history of retaining system, were used to check the validity of the proposed numerical modeling.

The used data is collected during excavation to construct the O7 station which is located on the orange line of the Kaohsiung Rapid Transit System (KRTS) in Taiwan [7]. The O7 excavation was rectangular in plan with dimensions of 178 m long by 22.7 m wide, and the maximum depth of the excavation was 21.7 m. The supporting system consisted of a diaphragm wall 1 m thick and 38 m deep, supported by five levels of H-beams steel struts with 4.5 m horizontal spacing on average. Fig.1-a shows the site monitored section that is considered in the current analysis.

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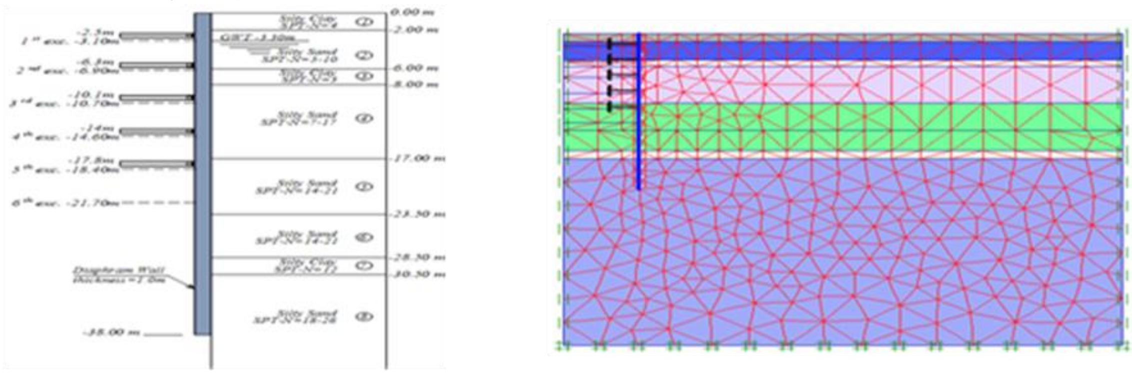
B. Finite Element Modeling

The above-mentioned case history was modeled using the software package PLAXIS, version 8.5 [8]. Two types of soil models were implemented, the Mohr-Coulomb (MC) and the Hardening Soil (HS) Models [9]. Table I presents properties of the soil layers in the project site.

Fig. 1-b shows the finite element mesh generated to model the case. The different soil layers were modeled using the fifteen node triangular elements. The supporting walls are modelled through 5-node lines element where a bending stiffness (EI) and an axial stiffness (EA) are introduced. The struts are modeled using fixed-end anchor having an axial stiffness of (AE). Soil-wall interfaces are modeled by using interface elements defined by five pairs of nodes.

Table I: Properties of soil layers of the case study.

Soil description	Layer thickness (m)	Density γ (kN/m^3)	Cohesion C_u (kN/m^2)	Friction Φ	Young's modulus E_u (kN/m^2)	Poisson ratio
Silty clay, grey	2.00	19.7	28	0	14000	0.49
Silty fine sand, grey	4.00	21.3	1	32	22810	0.30
Silty clay and fine sand, grey	2.00	20	21	0	10500	0.49
Silty fine sand, grey	9.00	21	1	32	39500	0.30
Silty fine sand, grey	11.50	20	1	33	51000	0.30
Silty clay, grey	2.00	19	84	0	42000	0.49
Silty sand with sandy silt folder, grey	Extended	20	1	34	64510	0.30



(a) (b)
Fig. 1. (a) Site monitoring section for the O7 station, [7], and (b) the generated finite element mesh.

C. Equivalent Section

Also, an equivalent one-layer section of soil was tested to assure that it performs like the actual multi-layer section. The equivalent properties including the modulus of elasticity (E), the angle of internal friction (ϕ) and the soil cohesion (C), were calculated as the weighted average for all the soil layers based on their thicknesses. Three concepts for the layer thickness, (H), (H^2) and (H^3), were considered to inspect the most reliable assumption. The properties of the investigated equivalent layers are shown in Table II.

III. RESULTS AND DISCUSSIONS

A. Verification of the Numerical Model

To verify the adequacy of the numerical modeling; a comparison between field measurements and finite element results from both models (MC and HS) was conducted. Figs. 2 and 3 reveal good agreement between the predicted and the monitored values of the maximum ground movements, with a little difference of about 4.0%, when adopting the hardening soil (HS) model. Whereas, the results of ground movement, using the Mohr-Coulomb (MC) model, showed a considerable difference, ranges from 10% to 40%, from the monitored value. So, the hardening soil model was considered in the conducted sensitivity analysis, [10].

B. Examining the Equivalent Section

Results of both lateral and vertical displacements, derived using equivalent soil properties, with those obtained using the original multilayer case were compared, Figs. 4 and 5. A good agreement was detected, especially when calculating the modulus of elasticity using the weighted average considering the layer height (H) rather than (H^2) or (H^3).

C. Sensitivity Analysis and Design Curves

A parametric study was performed to obtain design curves for the surface ground movement adjacent and around the deep excavation. The case study configuration was adopted in this study. Table III presents the soil parameters implemented in the numerical analysis of the reference cases.

Three retained soils with different elastic modulus ranges were considered in generating the design curves. For each soil type, the influence of the struts' vertical and horizontal spacings and the wall stiffness on the surrounding soil movements, was determined.

Table II: Properties of equivalent section.

Parameter	Units	1st Layer Along wall height (Equivalent)	2nd Layer The remaining part
γ_{sat}	kN/m^3	20.02	20.00
c_{ref}	kPa	7.67	1.00
φ	[deg.]	28.80	34.00
ψ	[deg.]	0.00	4.00
E_{50}^{ref}	MPa	Using (H) 43.30 Using (H^2) 47.18 Using (H^3) 48.48	64.51
E_{oed}^{ref}	MPa	Using (H) 43.30 Using (H^2) 47.18 Using (H^3) 48.48	64.51
E_{ur}^{ref}	MPa	Using (H) 129.90 Using (H^2) 144.57 Using (H^3) 145.43	193.53
ν_{ur}	[-]	0.20	0.20
$Power\ (m)$	[-]	0.80	0.50
p^{ref}	kPa	100	100
R_{inter}	[-]	0.67	0.67
R_f	[-]	0.90	0.90

Table III: Hardening Soil Parameters for the reference cases Set.

Parameter	Units	Retained soil (1)	Retained soil (2)	Retained soil (3)
γ_{sat}	kN/m^3	19.00	20.00	21.00
c_{ref}	kPa	1.00	1.00	1.00
φ	[deg.]	31.00	34.00	38.00
ψ	[deg.]	1.00	4.00	8.00
E_{50}^{ref}	MPa	(10.00-25.00)	(25.00-75.00)	(75.00-150.00)
E_{oed}^{ref}	MPa	(10.00-25.00)	(25.00-75.00)	(75.00-150.00)
E_{ur}^{ref}	MPa	(30.00-75.00)	(75.00-225.00)	(225.00-450.00)
ν_{ur}	[-]	0.20	0.20	0.20
Power (m)	[-]	0.50	0.50	0.50
p^{ref}	kPa	100	100	100
R_{inter}	[-]	0.70	0.70	0.70
R_f	[-]	0.90	0.90	0.90

- **Effect of soil modulus of elasticity**

The horizontal displacement curves of the wall, obtained using the three types of retained soils, are presented in Fig. 6. In addition, vertical ground movement profiles induced by soil adjacent to deep excavation that supported by multi-levels struts are presented in Fig. 7. From ground movement profiles, non-dimensional normalized curves were generated to describe the relationship between the ground movement and the distance perpendicular to the wall. By examining these normalized curves, two zones can be easily distinguished: The Primary zone, where settlement curve is steeper and buildings receive more influence, while in the Secondary influence zone, the curve is gentler and the influence on buildings is less, [5]. Those curves and their governing points are presented in Fig. 8 and Table IV.

- **Influence of Support Spacing**

Struts spacing has a significant effect on the performance of ground movements, the effects of varying the horizontal and vertical support spacing on the ground movement behavior of deep excavations are studied.

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The non-dimensional curves of settlement profiles shifted with significant values exactly at the primary influence zone. For the investigated cases, ground movement profiles

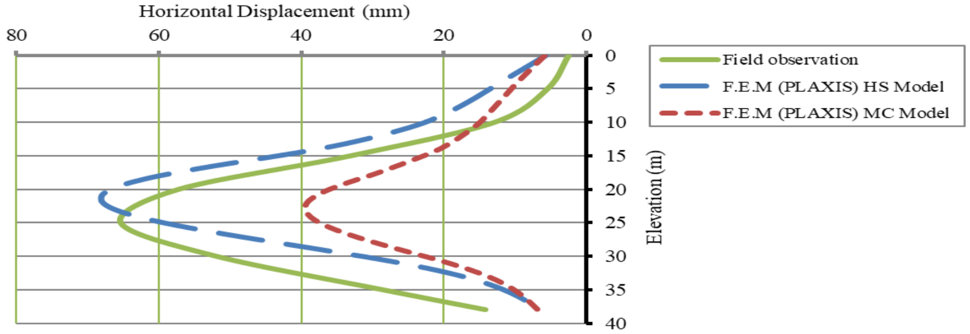

Fig. 2. Horizontal Displacements – Comparison between field observations and Finite Element Results (HS,

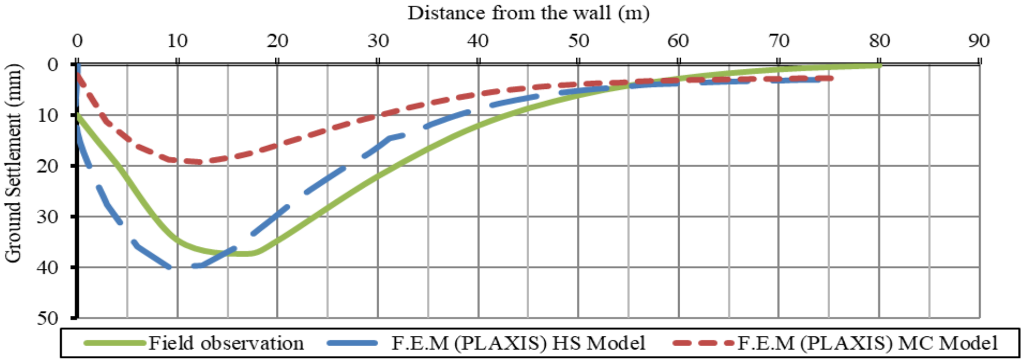

Fig. 3. Vertical Displacements – Comparison between field observations and Finite Element Results (HS,

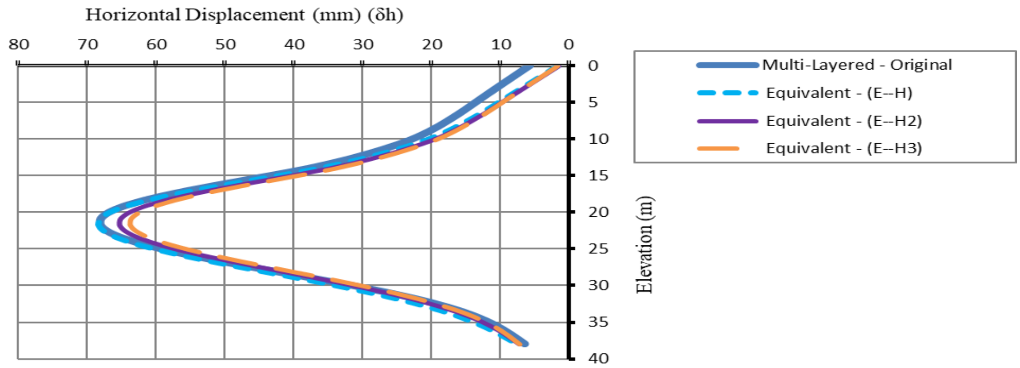

Fig. 4. Horizontal Displacement - Comparison between Multi-Layered and Equivalent Soil Models

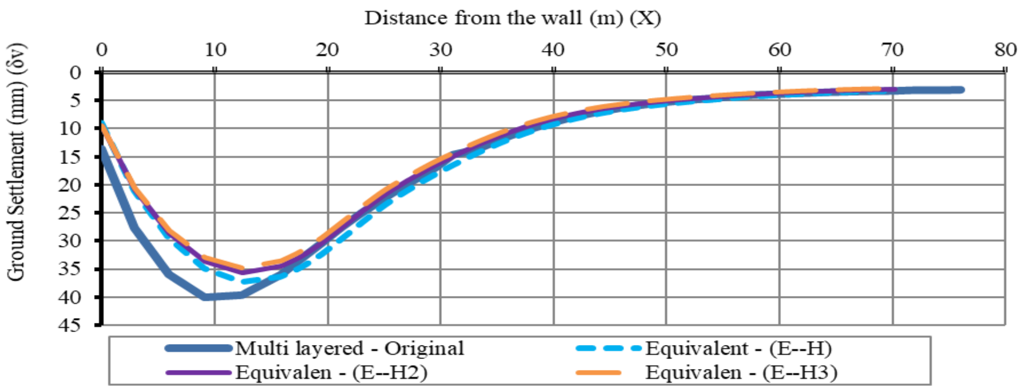

Fig. 1. Vertical Displacement - Comparison between Multi-Layered and Equivalent Soil

obtained from finite element analysis, then the obtained values

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analyzed and converted to non-dimensional normalized curves to each soil stiffness (different ranges of soil modulus of elasticity) to get a non-dimensional normalized curve used as a design chart for each soil stiffness.

Table IV: Coordinates of governing points of normalized idealized settlement curves - effect of Es

Soil Modulus of Elasticity Es (MPa)	Point	X/H	δv/H % = (y_i)	
10 ≤ Es < 25	P1	0.00	0.070	y1
	P2	0.60	0.250	y2
	P3	2.10	0.050	y3
25 ≤ Es < 75	P1	0.00	0.040	y1
	P2	0.50	0.120	y2
	P3	2.00	0.025	y3
75 ≤ Es < 150	P1	0.00	0.030	y1
	P2	0.40	0.060	y2
	P3	1.50	0.005	y3

1) *Horizontal support spacing*

The horizontal spacing was changed from 0.67 to 1.78 times the original horizontal spacing (4.5 m). Figs. 9 and 10 show the curves for soil with (E=10 to 25MPa), Figs.11 and 12 show the curves for soil with (E=25-75MPa), Figs. 13 and 14 show the curves for soil with (E=75 to150MPa). As shown in the figures, ΔS_h represents the difference between horizontal spacing for original case (S_{hi}) and the final spacing adopted on the analysis (S_h).

2) *Vertical support spacing*

The vertical spacing changing from 0.67 to 1.78 times the original vertical spacing, forming 3, 4, 5 and 7 levels of struts. Figs. 15 and 16 show the curves for soil with (E_s=10 to 25MPa), Figs. 17 and 18 show the curves for soil with (E_s=25 to 75MPa) and Figs. 19 and 20 show the curves for soil with (E_s=75 to 150MPa). Where ΔS_v represents the difference between horizontal spacing for original case (S_{vi}) and final spacing performed on the analysis (S_v), as presented in the figures.

▪ ***Influence of Wall Stiffness***

A parametric study was performed taking into consideration the wall stiffness in the form of $EI = (H/L)^A \ EI_{original}$, where EI is the wall flexure rigidity, H is the excavation depth, L is the wall height and (A) power varied from 20.40 to 34.00 to simulate types of wall rigidity as a function of wall height and excavation depth. The results obtained from the finite element analysis are presented in Figs. 21 & 22 for soil has Es=10-25 MPa, Figs. 23 & 24 for soil has Es=25-75 MPa, and finally Figs. 25 & 26 for soil has Es=75-150 MPa.

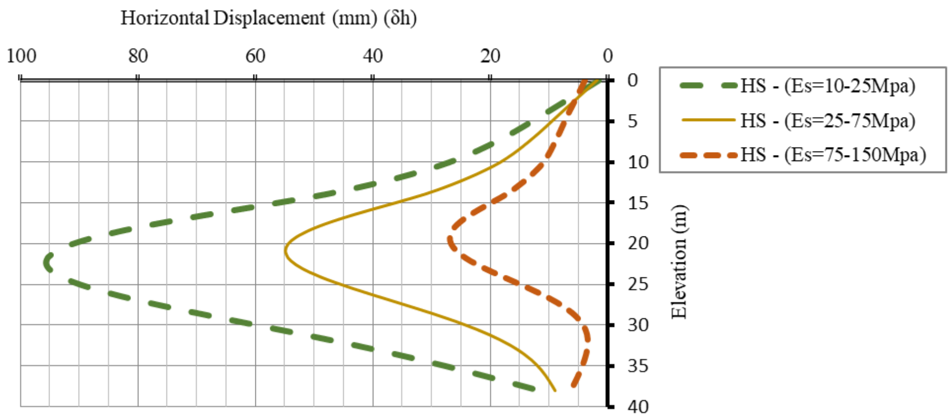

Fig. 6. Effect of changing soil modulus of elasticity (Es) on

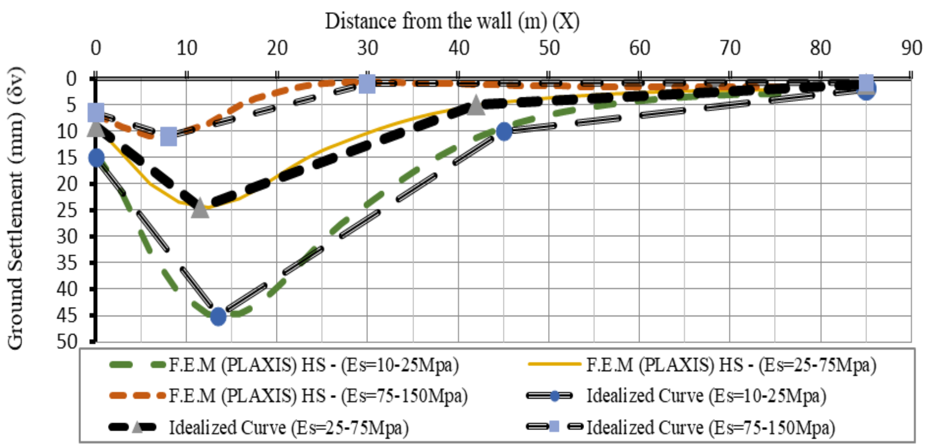

Fig. 7. Effect of changing soil modulus of elasticity (Es) on settlement – Idealized

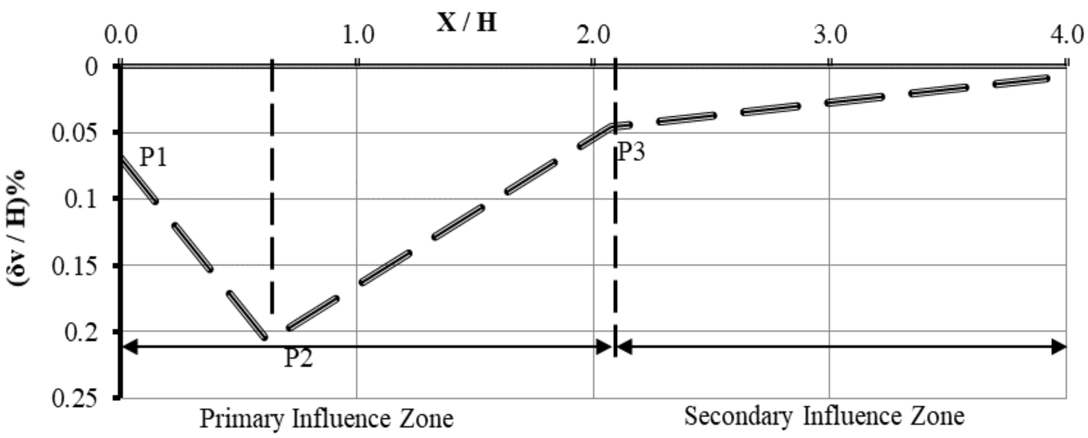

Fig. 8. Effect of Es on settlement – Non-dimensional normalized curve.

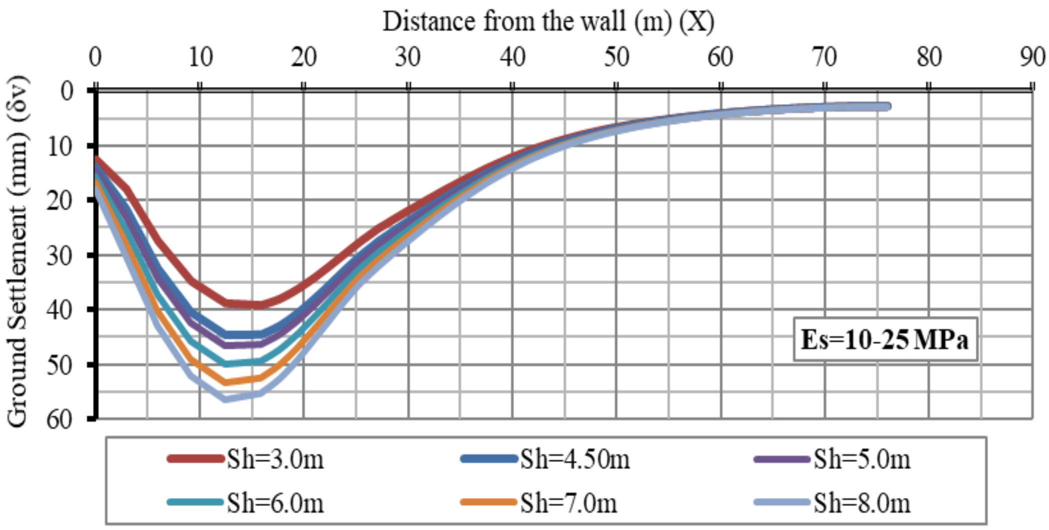

Fig. 9. Effect of support horizontal spacing on settlement, (Es=10-25 MPa)

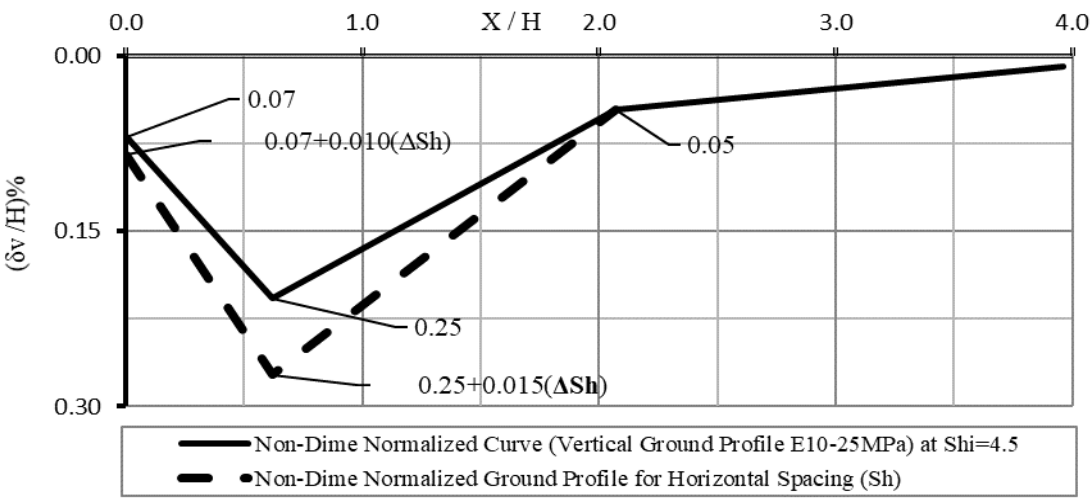

Fig. 10. Effect of support horizontal spacing on settlement – Normalized curve, (Es=10-25 MPa)

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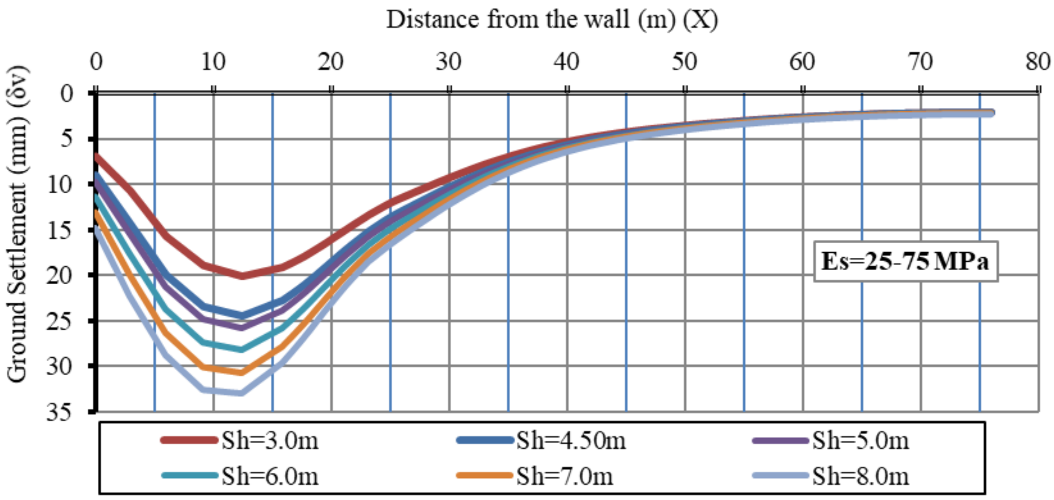

Fig. 11. Effect of support horizontal spacing on settlement, (Es=25-75 MPa).

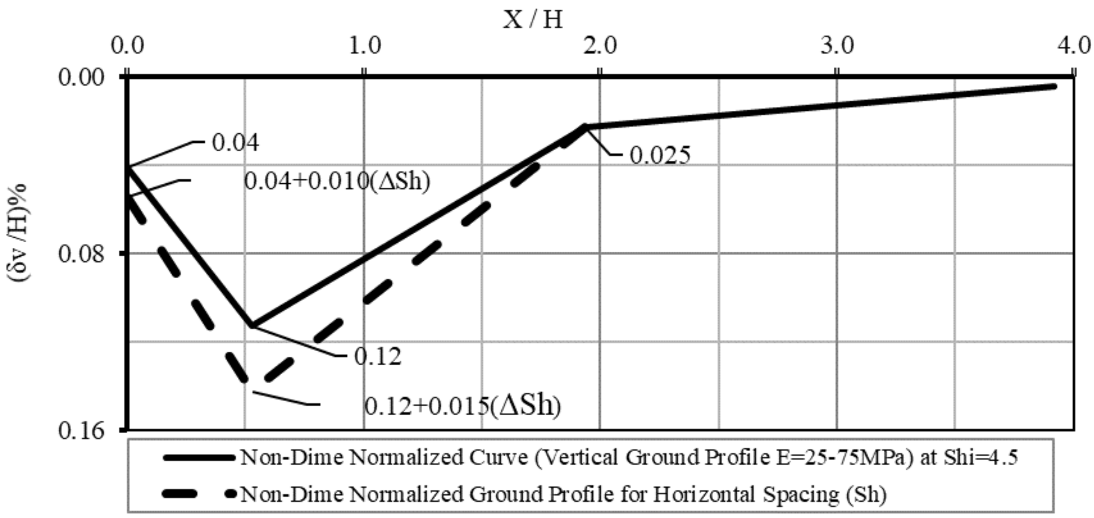

Fig. 12. Effect of support horizontal spacing on settlement – Normalized curve, (Es=25-75 MPa)

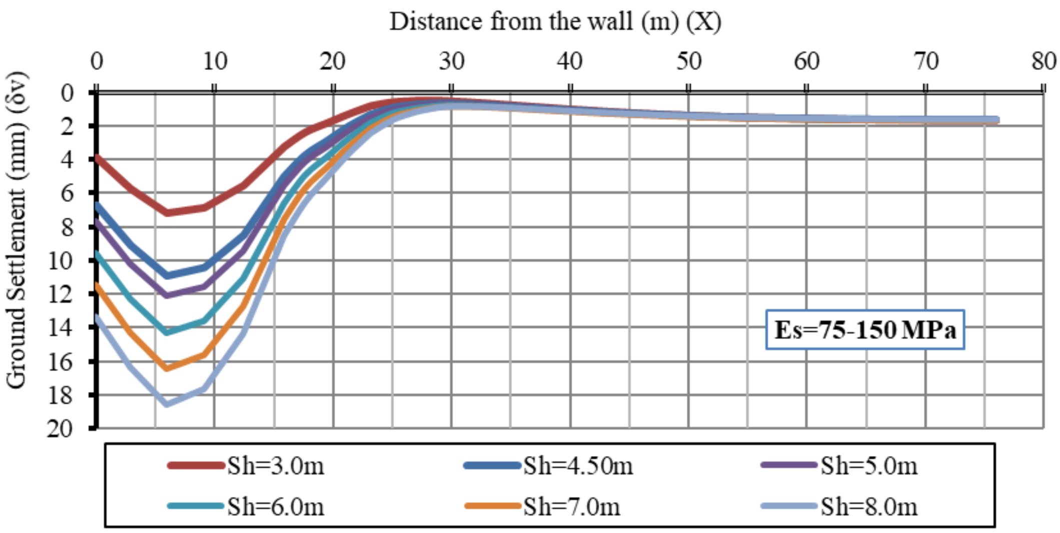

Fig. 13. Effect of support horizontal spacing on settlement, (Es=75-150 MPa)

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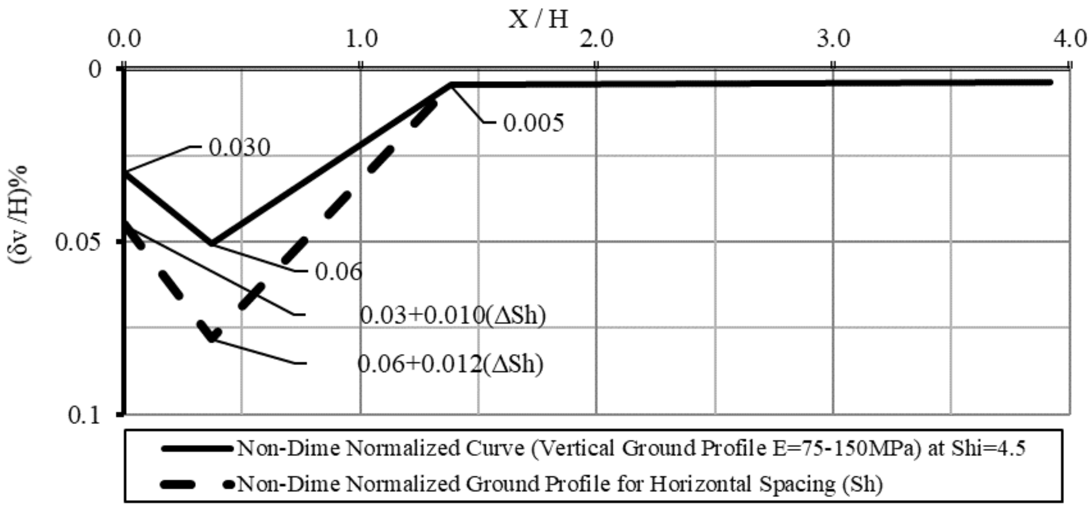

Fig. 14. Effect of support horizontal spacing on settlement –Normalized curve, (Es=75-150 MPa)

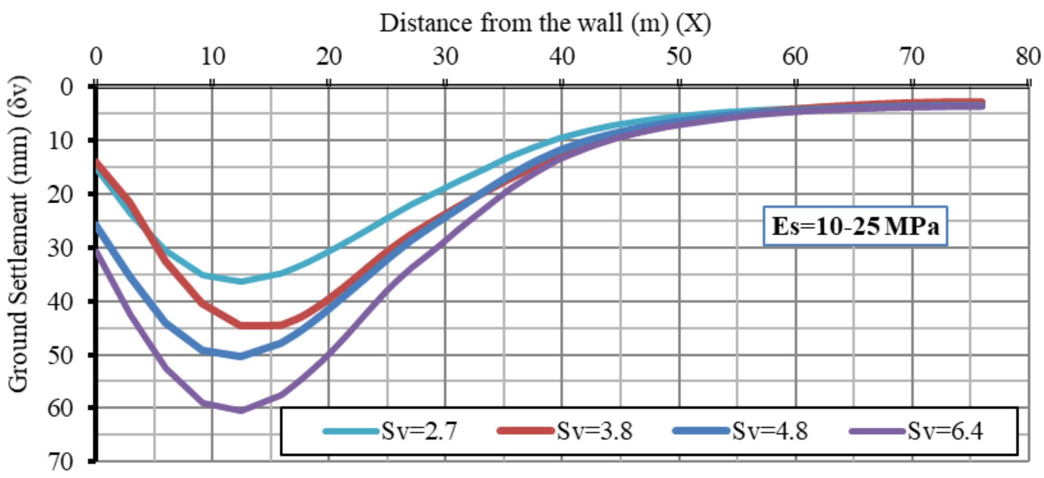

Fig. 15. Effect of support vertical spacing on settlement, (Es=10-25 MPa)

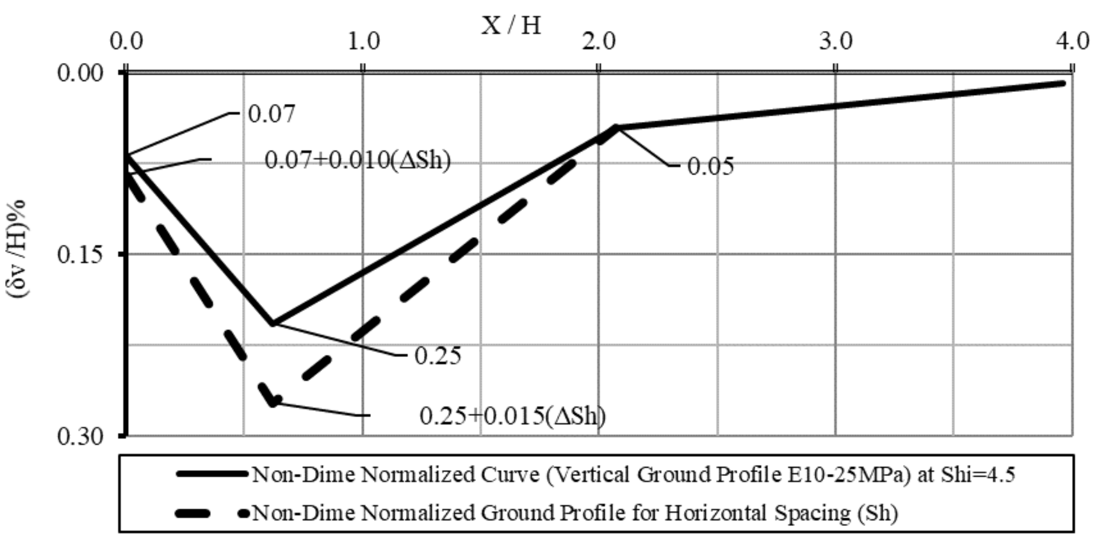

Fig. 16. Effect of support vertical spacing on settlement – Normalized curve, (Es=10-25 MPa)

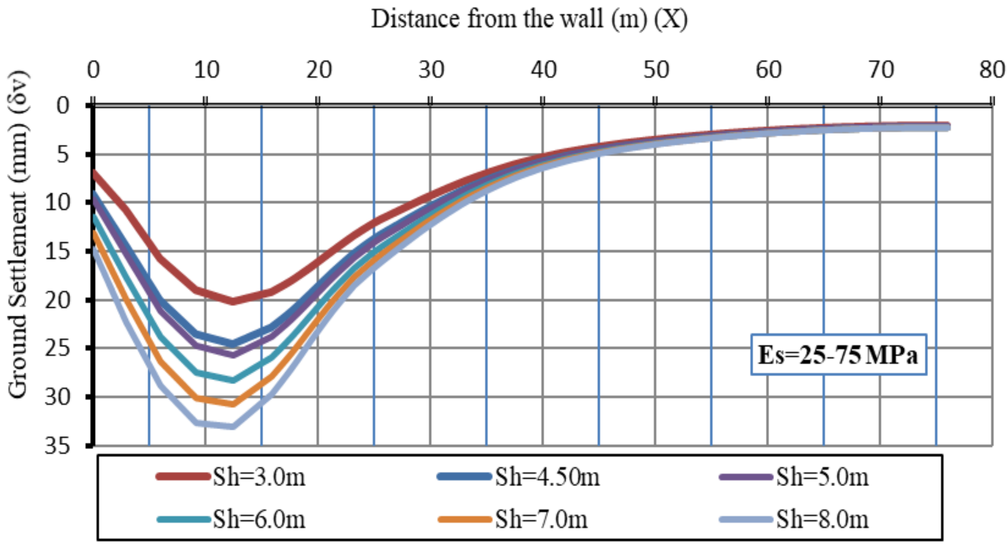

Fig. 17. Effect of support vertical spacing on settlement, (Es=25-75 MPa)

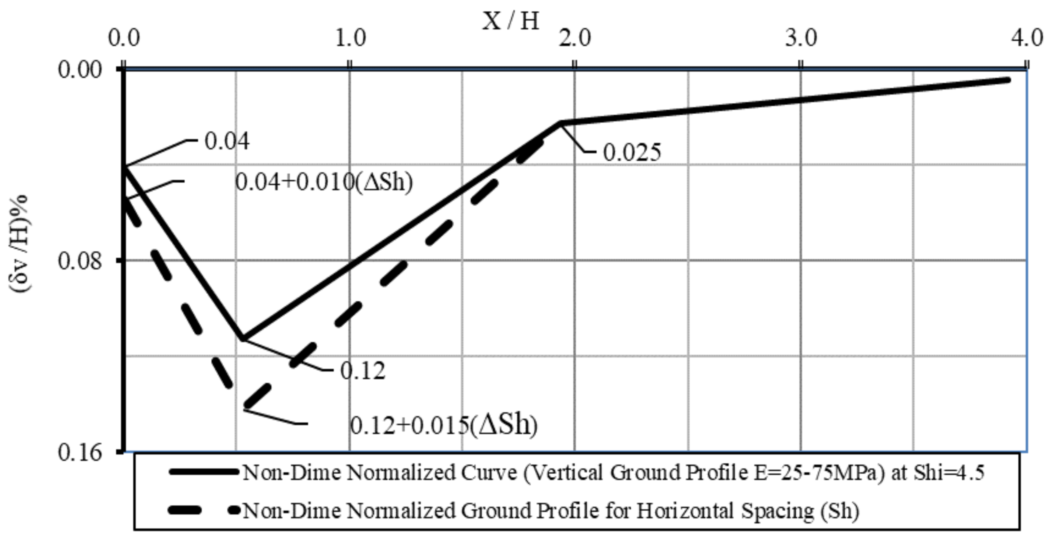

Fig. 18. Effect of support vertical spacing on settlement – Normalized curve, (Es=25-75 MPa)

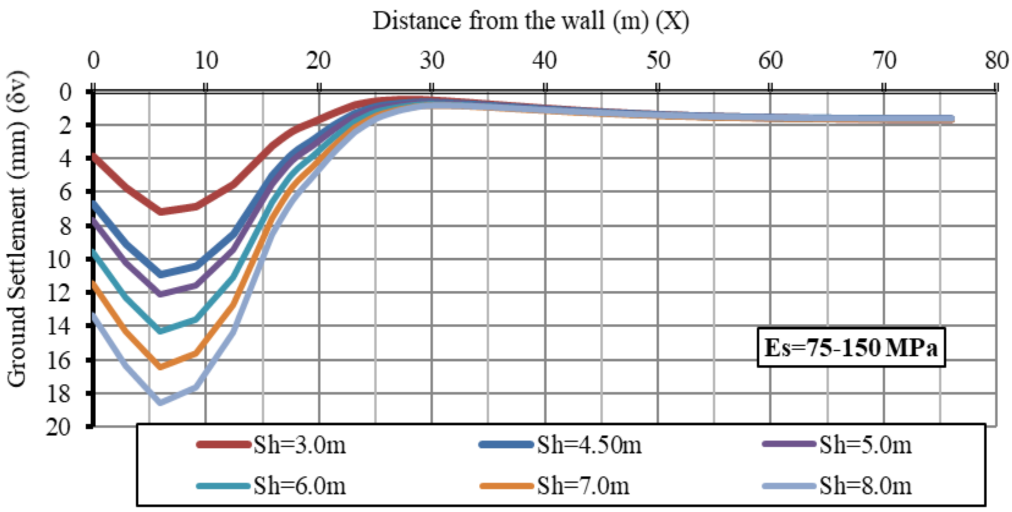

Fig. 19. Effect of support vertical spacing on settlement, (Es=75-150 MPa)

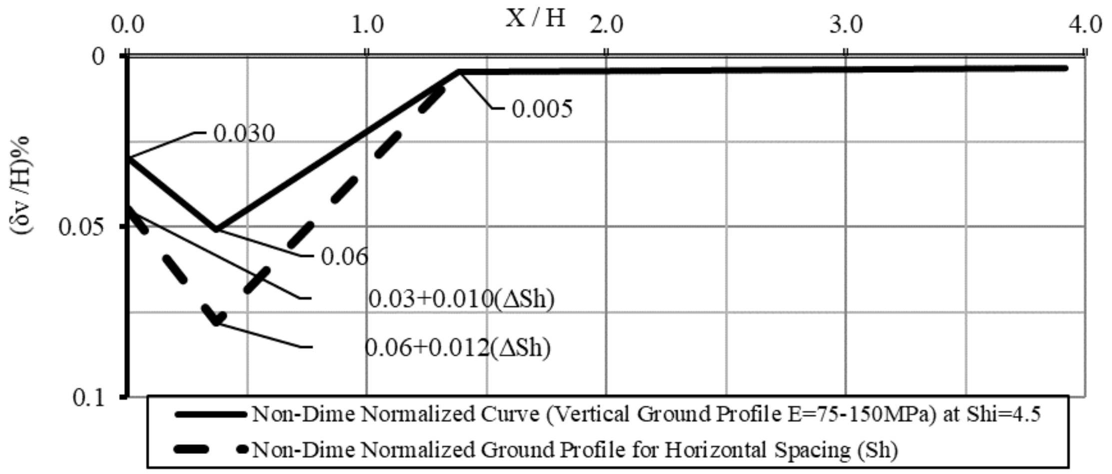

Fig. 20. Effect of support vertical spacing on settlement – Normalized curve, (Es=75-150 MPa)

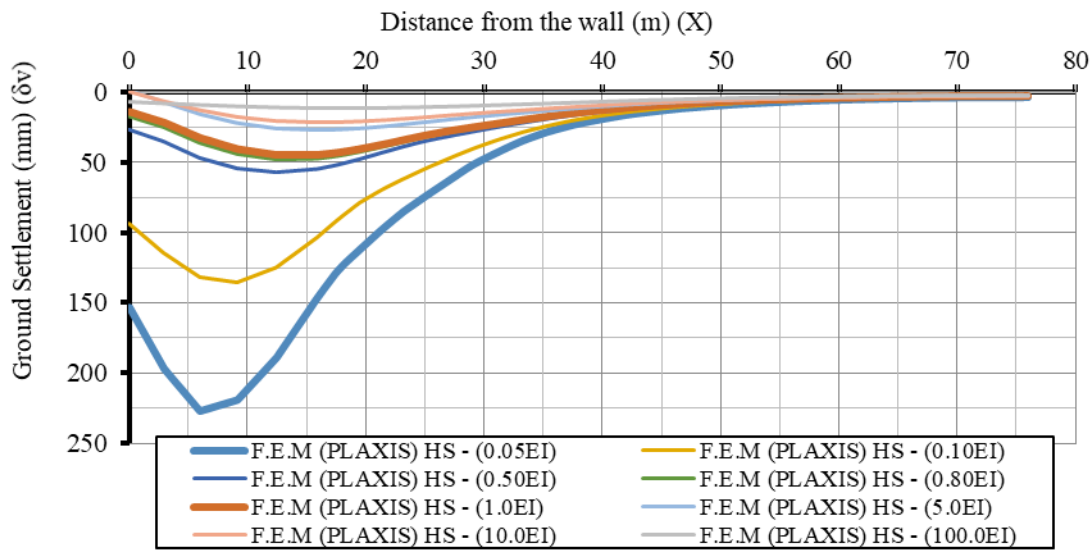

Fig. 21. Effect of wall stiffness on settlement, (Es=10-25 MPa).

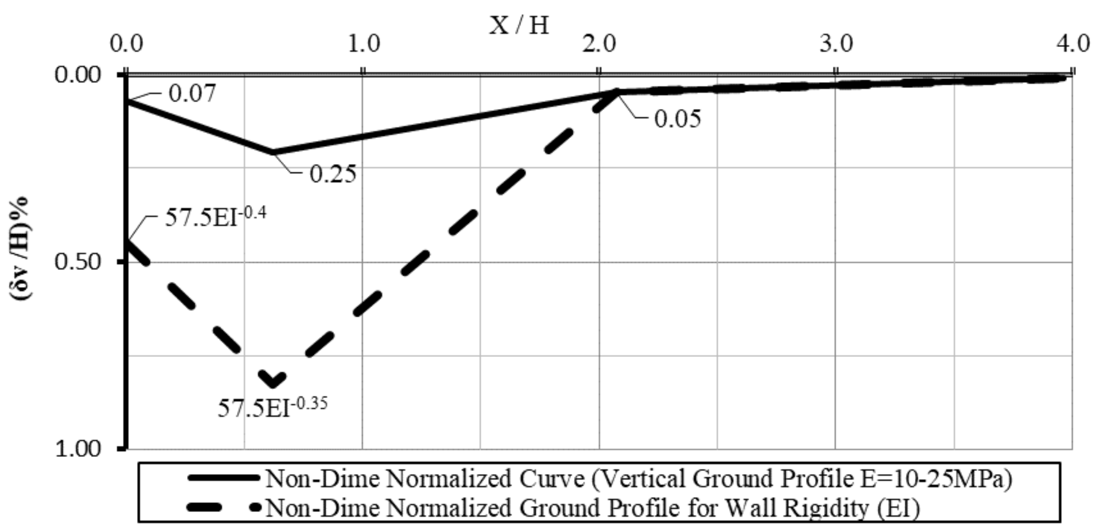

Fig. 22. Effect of wall stiffness on settlement – Normalized curve - (Es=10-25 MPa).

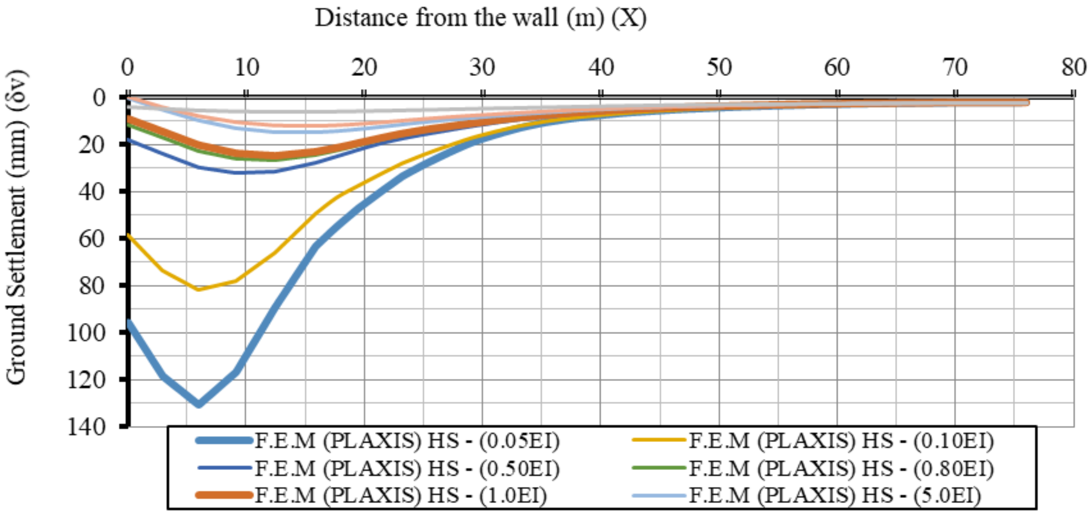

Fig. 23. Effect of wall stiffness on settlement – Normalized curve, (Es=25-75 MPa)

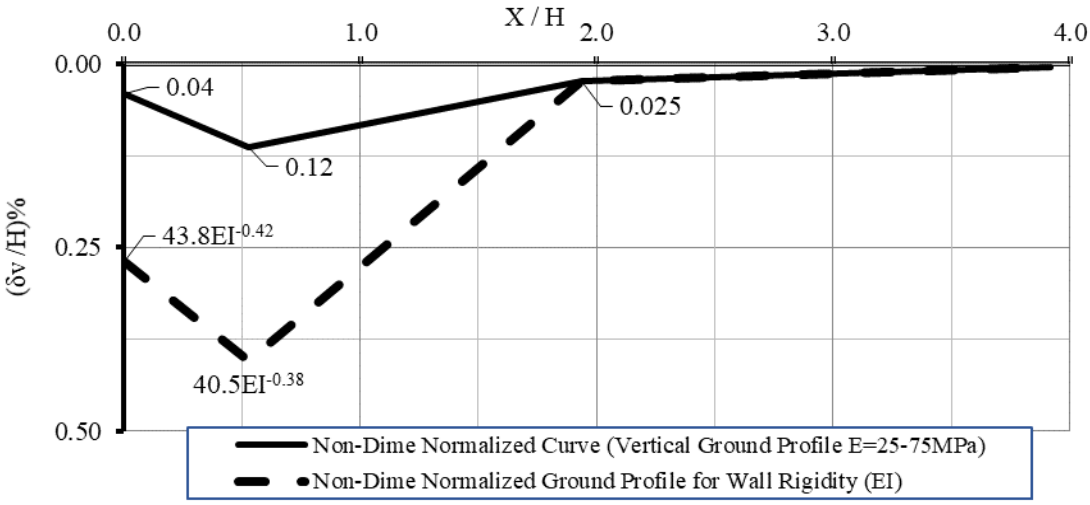

Fig. 24. Effect of wall stiffness on settlement – Normalized curve, (Es=25-75 MP)

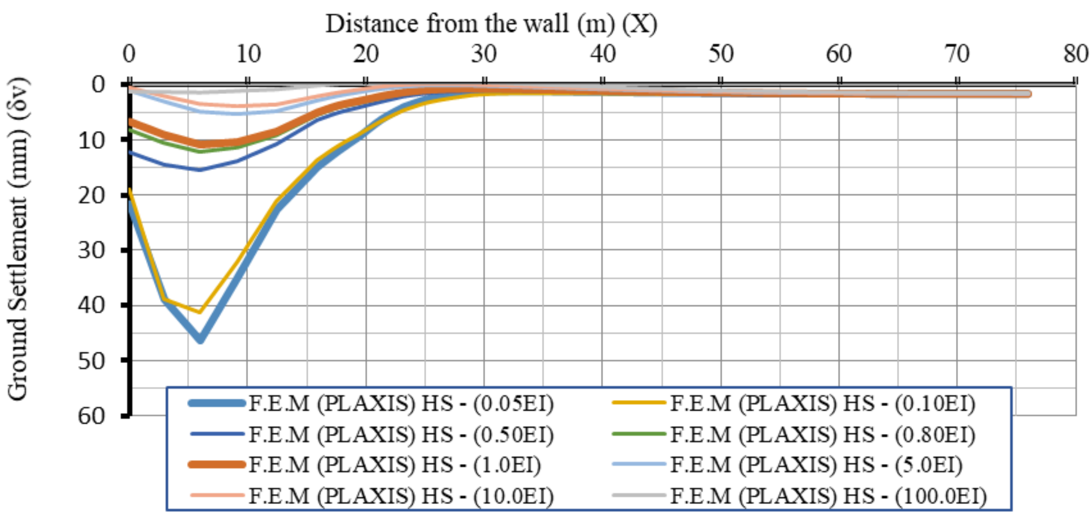

Fig. 25. Effect of wall stiffness on settlement – Normalized curve, (Es=75-150 MPa)

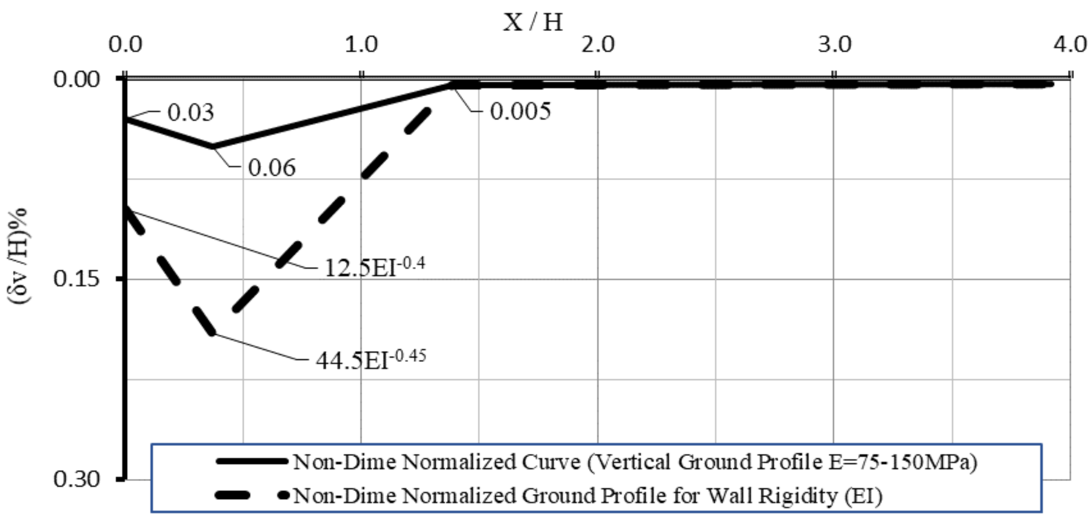

Fig. 26. Effect of wall stiffness on settlement – Normalized curve, (Es=75-150 MPa)

IV. PROPOSED SYSTEM STIFFNESS CHARTS

The design procedure presented by Clough et al. [6] was considered – for a long time - as the state-of-the-practice for selecting the most appropriate excavation support stiffness. This design procedure uses a chart that allows the user to estimate maximum lateral wall movements as a function of effective system stiffness and the factor of safety against basal heave, in circumstances where displacements are primarily a result of the excavation and support process. Long [11] and Moormann [12] assessed the validity and applicability of the Clough et al. design chart [6]. Also, Zabata-Medina [13] developed work of Clough et al. [6].

In this research work, a stiffness ratio (R) which represents the stiffness of the supporting system is suggested. It was developed from parameters that affect the overall stiffness of an excavation support system. The parameters are as follows:

$$R = f\,(E,I,d,S_v,S_h) \qquad (1)$$

Where (E) is Young's modulus of the material of wall, (I) is moment of inertia per unit length of the supporting wall, (S_h) is average horizontal distance between support, (S_v) is average vertical distance between supports, (d) is penetration depth and (γ_w) unit weight of water in order to control the units. From an inspection of the variables contributing to system stiffness and data analysis, it can be noticed that every parameter studied has either positive or negative effect with a special weight. We suggest the new stiffness parameter with the form of:

$$R = \frac{EI.d}{S_v^4.S_h^2.\gamma_w} \qquad (2)$$

By combining the data obtained from the previous analyses, and using regression analysis, it was found that there is a relationship between the stiffness parameter (R) and maximum of the percentage of vertical displacement to depth of excavation (δv/H %). Best fit of scattering produces three new curves that relates the system stiffness (R) with surface ground movement induced by deep excavation by the values y1 and y2 which represent the maximum value of percentage of vertical displacement to depth of excavation for different types of soil as shown in Figs. 27 to 29.

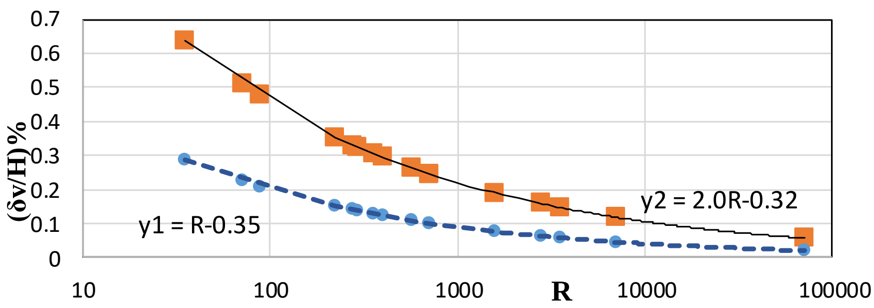

Fig. 27. Relationship between (R) and (y1) and (y2), (Design curve for: Es=10-25 MPa).

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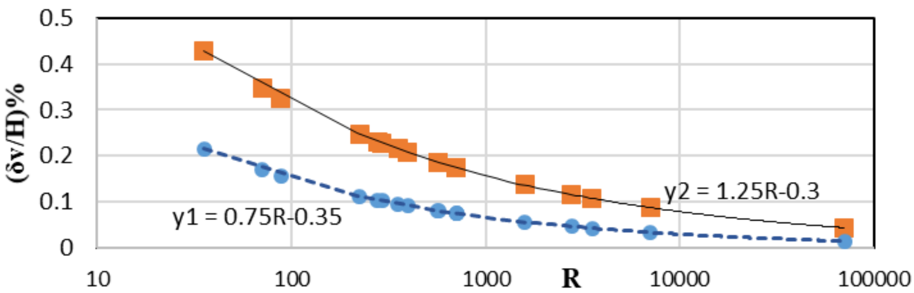

Fig. 28. Relationship between (R) and (y1) and (y2), (Design curve for: Es=25-75 MPa).

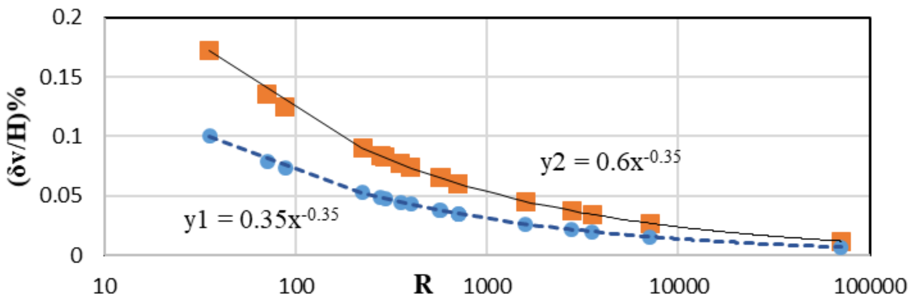

Fig. 29. Relationship between (R) and (y1) and (y2), (Design curve for: Es=75-150 MPa).

V. CONCLUSIONS

- Finite Element Method (FEM) is a powerful tool to simulate the performance of deep excavation supporting system. The Hardening Soil (HS) model produced more accurate results than Mohr-Coulomb model (MC), when compared with field observations.
- Sensitivity analysis of a case study representing deep excavation showed that the spacing between supports and the wall stiffness have a significant effect on ground movements induced by deep excavation.
- An equivalent one-layer section of soil can perform nearly as a multi-layer section, with a small difference ranging between (5.0 to 10.0%). Hence, equivalent engineering properties including modulus of elasticity (E), angle of internal friction (ϕ) and cohesion (C) for the multi-layer section, calculated as the weighted average for all soil layers, can perform well in the analysis and design of the excavation support systems.
- Good agreement was detected, when calculating the modulus of elasticity using the weighted average considering the layer height (H) rather than (H^2) or (H^3).
- Predicted numerical results have been employed to construct normalized non-dimensional design charts that represent different soil types, considering variable wall rigidity and variable support spacing.
- The new parameter, stiffness ratio (R), derived for the support system, was adopted, to develop the new design charts and equations that can be used to predict the ground surface profile induced by deep excavation.

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