Study of Loose Soil Layer Effects on Excavations Supported by Steel Sheet Pile Walls-A Numerical Study

Behrouz Ahmadpour[1], Masoud Amel Sakhi[*1], Mohsen Kamalian[2]

1. Faculty of Engineering, Department of Civil Engineering, Qom University of Technology
2. International Institute of Earthquake Engineering and Seismology (IIEES)

Received: 9 Nov 2016 Accepted: 14 Oct 2017

Abstract

Steel sheet pile walls are being widely used as earth retaining systems. Sometimes loose or soft soil layers are located in various depths in an excavation. This issue causes different effects on ground surface displacements, forces and moments acting on sheet piles and struts during excavation procedure, compared with a status that soil is totally uniform. These differences are not exactly considered in conventional design methods of sheet pile walls. In this paper, a deep excavation using finite element method is analyzed. Excavation's depth is divided into three different layers. One of three layers is a loose soil layer and its position is modeled in three different situations, top, middle and bottom of the model.

[*]Corresponding author: mamelsakhi@yahoo.com

[DOR: 20.1001.1.22286837.1397.12.5.2.4]

[DOI: 10.18869/acadpub.jeg.12.5.31]

Obtained results are compared with results of excavation without the loose layer. The pseudo-static analysis is performed by applying 0.3g horizontal acceleration. The results indicate that when a loose layer is located beneath stiffer layers, bending moments acting on sheet pile wall and shear forces increase about (50~100)% and (15~50)%, respectively. Also, the middle loose layer changes the location of maximum lateral deformation of steel sheet pile wall.

Keywords: Excavation, sheet piling, loose layer, strut

[DOR: 20.1001.1.22286837.1397.12.5.2.4]

[DOI: 10.18869/acadpub.jeg.12.5.31]

Introduction

Excavation process is an important part of civil engineering problems, for example, foundations or basements of high rise buildings, underground oil tanks, subways or mass rapid transit systems, tunnels, etc. Significant increases of research effort have been observed during recent years on deep supported excavations in the urban areas. One of the most commonly used systems to support deep excavations includes reinforced concrete systems, e.g. diaphragm walls or pile walls, steel sheet pile walls and soil mix pile walls. In sheet piling method, steel sheet piles are driven into soil and also by excavation operation progress, required struts are installed (Ou, 2006).

For a safe and successful deep excavation, behaviours of excavation support system and the adjacent ground must be considered during design and operate. For a deep excavation in soft soil, behaviors are related to different factors (Peck, 1969; Mana and Clough, 1981). The deformation feature of a retaining system depends not only on characteristics of the excavated soils but also on the underlying layers. Studies on multi-layered soils overlying rock showed relatively small deformation (Wong et al., 1997; Yoo, 2001 and Long, 2001). The low strength of the retained soils and the thickness of the soft soil layers are the most prominent factors in controlling the deformations. The most positive bedrock's influence may be overshadowed by low strength of soils if the soft soil layer thickness is large enough (Ma et al., 2010).

The behavior of a deep excavation support system is described and analyzed using a number of quantities, including the displacements of wall elements and earth pressure distribution, movement of soil masses surrounding the excavation, the movement of existing adjacent structures, and the forces acting on the lateral support elements. The research effort towards the evaluation of the above quantities follows, in general, three main directions: performance of numerical and theoretical analyses (Zdravcovic et al., 2005), testing physical models of small and medium scale (Son and Cording, 2005; Laefer et al., 2009) and collecting performance data from instrumented large (i.e. natural) scale deep excavation projects (Long, 2001; Leonidou et al., 2001; Moorman, 2004; Zekkos et al., 2004).

Evaluation of vertical bearing capacity of sheet pile foundations is based on conventional analyses for piles (Terzaghi and Peck, 1996; USACE, 1991). The structural capacity of the sheet pile considers combined axial loading and/or eccentric loading due to uniform wall loads and point loads, together with bending moments due to the lateral earth pressure. The structural analysis treats the sheet pile foundation as a steel column subject to axial loads and bending moments (Underwood and Greenlee, 2010).

In some cases of civil engineering projects anchored sheet pile walls are needed to be installed on slopes. Conventional methods used in the design of anchored sheet pile walls are based on the limit equilibrium approach and they do not consider processes involved during construction. The sheet pile walls constructed on slopes may require both cut and fill operations. Varying amounts of cut and fill sections cause different loading and unloading of soils around the wall resulting in different wall behavior. Study results of Bilgin and Erten by Finite Element Method showed that the location of anchored sheet pile wall along the slope has a significant effect on wall behavior. For example, anchor forces decrease significantly, approximately 30 percent when the wall moves from the top of the slope to the tip of the slope (Bilgin and Erten, 2009). Bilgin (2012) considered lateral earth pressures on anchored sheet pile walls. Although the existence of stress concentration at the anchor level, the conventional design methods do not consider the stress concentrations along the wall height, and they assume that lateral earth pressures linearly increase with depth. Because the whole design depends on the lateral earth pressures, a design based on an inaccurate earth pressure distribution will result in designs that are either conservative or, more importantly, unsafe. A Comparative parametric study using the conventional design method and the FEM was performed to investigate the lateral earth pressures, bending moments, and anchor forces of single-level anchored sheet pile walls in cohesionless soils. According to obtained results, neither active nor passive earth pressures linearly increase with depth as assumed in conventional design methods. Also, the conventional design methods resulted in approximately 50% more wall bending moments compared with the FEA results but the anchor forces obtained from the FEAs were approximately 40% more than the ones obtained from the conventional design method.

Sahajda (2014) considered the determination of anchor loads. In this study, the measurement was carried out on a sheet pile wall supporting an excavation in mixed clay/sand soil. The forces measured were in average 68 % of the values calculated in the design with the assumption of fully drained conditions in clay. The calculation made with undrained clay led in turn to calculated forces significantly smaller than measured. Since this lies on the unsafe side, it is not recommended to assume undrained conditions in firm and stiff clay. The actual anchor forces were shown to depend more on the value of the lock-off load than e.g. surface load at the retained side.

Athanasopoulos et al. (2011) studied on the performance of a steel sheet pile wall for excavation supporting system in the urban environment. In this study considered data pertaining to a temporary deep supported excavation, constructed in the urban environment of Patras, Greece. Obtained results say laterally supported steel sheet pile walls installed by vibratory drivers, can be used safely for earth retention in the sensitive urban environment, provided that the site stratigraphy does not include thick sand-gravel layers and a systematic monitoring of generated ground vibrations is performed during driving.

In order to achieve a safe and stable structure, modifications are required to design sheet pile walls because of uncertainty in variables. GuhaRay and Baidya (2015) studied on reliability-based analysis of cantilever sheet pile backfilled with different soil types using the finite-element approach. Results of this study indicate the cohesion of the foundation soil is found to be the most sensitive parameter.

Loose layer location may have different effects on forces acting on sheet pile wall and strut system. This issue has not investigated comprehensively yet in studies related to sheet pile walls. Authors previous studies in clay deposits show that existence of loose layer in the bottom of stiff layers increases struts axial forces and sheet piles bending moments (Ahmadpour et al., 2015; Ahmadpour and Amel Sakhi, 2016). Other previous studies show that for retaining walls that retain a significant thickness of soft material, maximum lateral and vertical movements values increase significantly from the stiff soil cases (Long, 2001).

In this study an excavation with the sheet piles supporting system is considered and by using PLAXIS finite element software, effects of the loose layer on soil deformation and sheet piles lateral supporting systems are studied. Because of the importance of maximum lateral deformation location and its effects on adjacent building and facilities, in the following, this issue is studied. Previous researchers have sufficed into instrumental and experimental data.

Modelling Verification

In order to verify the model, a comparison between research of Bilgin and Erten (2009) and a PLAXIS software modeling is performed and obtained results are compared with each other. Figures 1 and 2 show lateral displacement and bending moment acting on sheet pile wall, respectively. Comparison between this study and results of past researchers shows good coincidence.

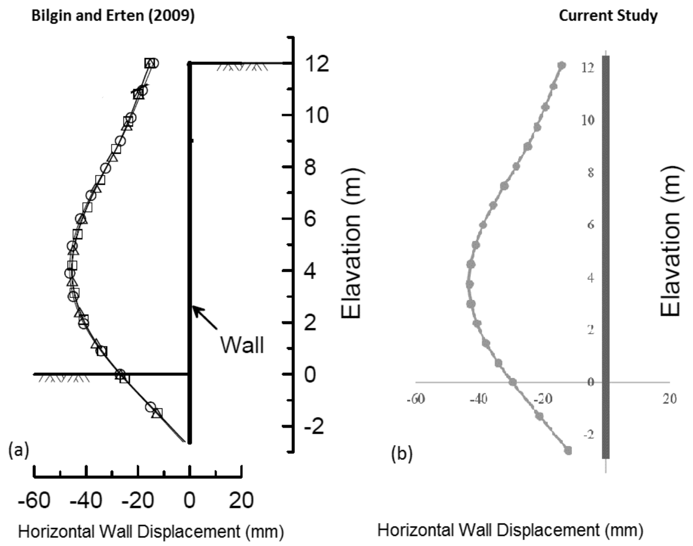

Figure 1. Lateral displacement of sheet pile wall

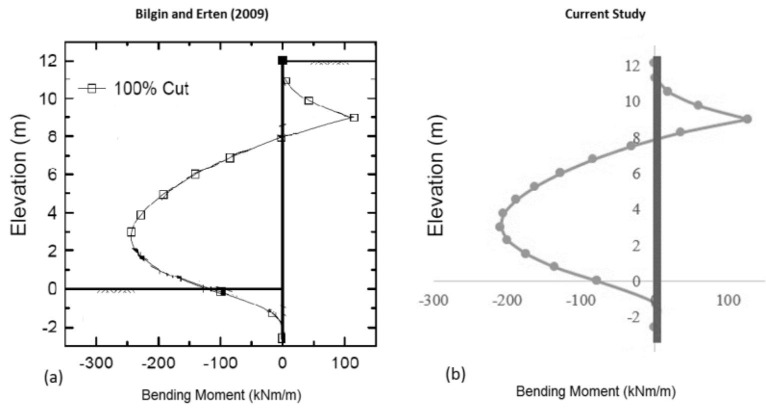

Figure 2. Bending moment acting on sheet pile wall

Model Specifications

1. Geometry

Width and depth of considered excavation are 10 and 12 meters, respectively. The longitudinal direction of excavation is so long that plain strain is considered in modeling. Due to the symmetry, half of the project's geometry is modeled. The final length of steel sheet piles is 16 meters. The first strut is installed beneath one meter of the ground surface and subsequent struts are modeled in 3 meters spacing from each other so that finally, four struts are considered along with the depth of excavation. Struts spacing in the longitudinal direction of excavation is 5 meters. Overburden on the ground surface is 5 kN/m^2. The soil profile is modeled by four layers. The thickness of three up layers is 4 meters. The fourth gravel layer thickness that the sheet piles penetrate through it, is 13 meters (Figure 3). Three top layers are considered clayey and sandy in separated models. In saturated cases, groundwater level is 1 m beneath the ground surface. One layer of three clayey or sandy layers is considered loose that its location changes in different models and its effects are studied.

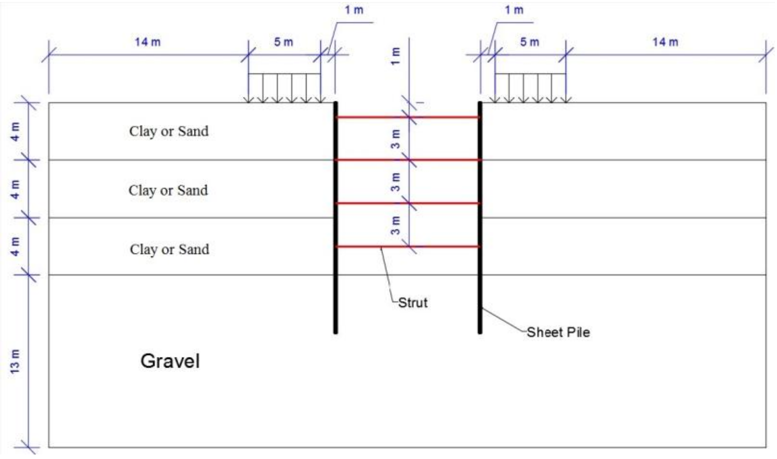

Figure 3. Model geometry

2. Materials

Table 1 presents soil properties used in this study. Mohr-Coulomb constitutive model is used in the analysis.

Table 1. Soil Parameters (Das, 2013)

Soil type		Loose Clay	Stiff Clay	Loose Sand	Stiff Sand	Gravel
Soil Properties	γ (kN/m^3)	12	17	15	18	18
	γ_{sat} (kN/m^3)	17	19	19	21	22
	E (kN/m^2)	3000	12000	20000	50000	90000
	υ	0.2	0.4	0.3	0.35	0.45
	c (kN/m^2)	10	70	1	1	1
	ϕ (°)	10	25	30	40	40
	R	0.5	0.5	1	1	1

Table 2. Elements Properties

Element	Profile	E (kN/m^2)	EA	EI (kNm^2/m)
Sheet pile	PZ40	2×10^8	4.98×10^6 (kN/m)	1.341×10^5
Strut	HP 200×53	2×10^8	1.368×10^6 (kN)	-

[DOR: 20.1001.1.22286837.1397.12.5.2.4]

[DOI: 10.18869/acadpub.jeg.12.5.31]

3. The Finite Element Modeling

Four different models are considered (Figures 4-7). In pseudo static analyses, 0.3g horizontal acceleration is considered for all models. The soil layers were modeled using 15-node triangular elements. The 15-node elements PLAXIS software applies fourth-order interpolation for displacements, and the numerical integration involved 12 stress points. A typical finite element model mesh consisted of 1170 elements and 9715 nodes. In order to increase the accuracy, a finer mesh is used near sheet pile wall. The average element size is 731.5×10^{-3} m. The soil excavation was simulated by removing soil in lifts. The total soil depth removed was performed in some phases.

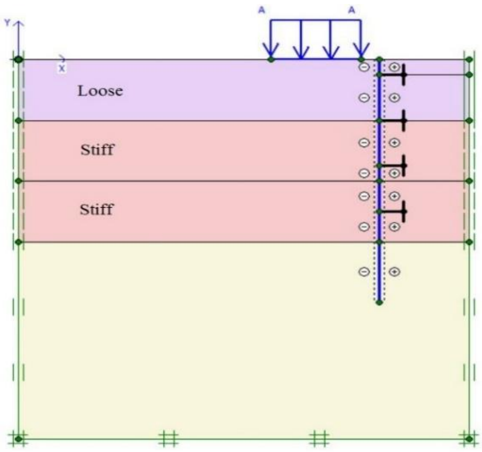

Figure 4. Excavation model with top loose layer (Model 1)

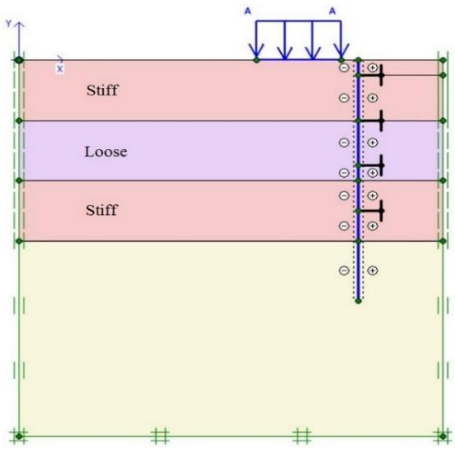

Figure 5. Excavation model with middle loose layer (Model 2)

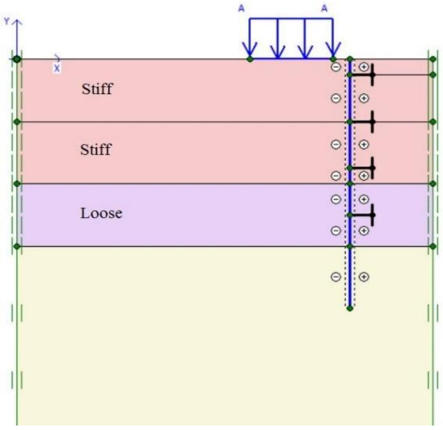

Figure 6. Excavation model with bottom loose layer (Model 3)

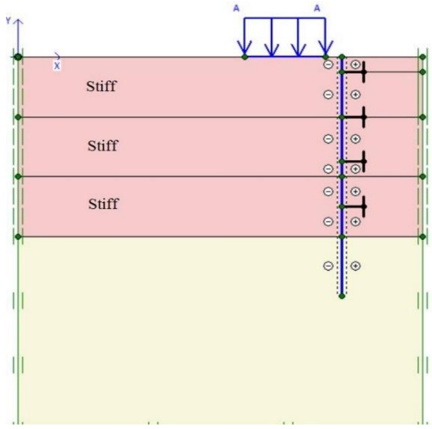

Figure 7. Excavation model without loose layer (Model 4)

Numerical Results

Deformed shape of model No. 4 is shown in Figure 8. Equation (1) represents the change percent of different parameters obtained in models 1, 2 and 3 in comparison with model No. 4.

$$\frac{U_i - U_1}{U_1} \times 100 \qquad (1)$$

Where U_i is the value of relevant parameters (stress, displacement or force) in models with loose layer and U_1 is the value of parameters in the model without the loose layer. Obtained results are shown in Figures 9-20. It should be mentioned that St = Static analysis, PS = Pseudo static analysis, D=Dry situation and S = Saturated situation results.

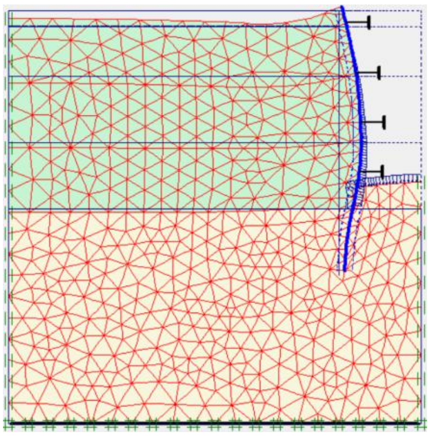

Figure 8. Deformation in model No. 4

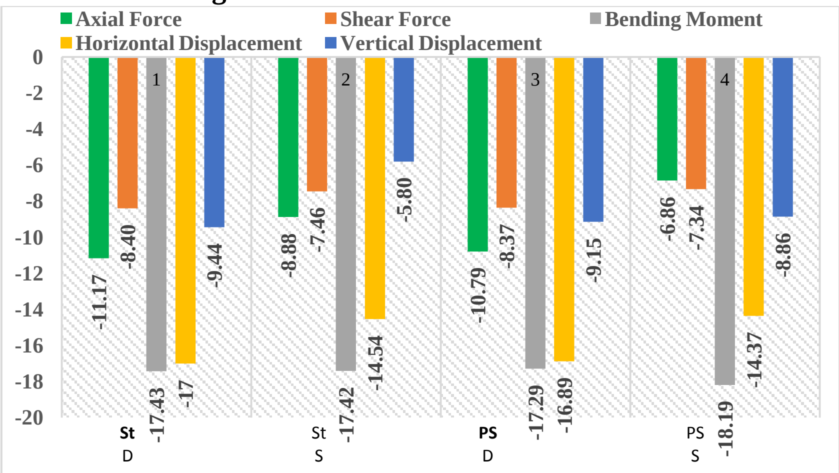

Figure 9. Sheet pile parameters changes in percent – Clay (model No. 1)

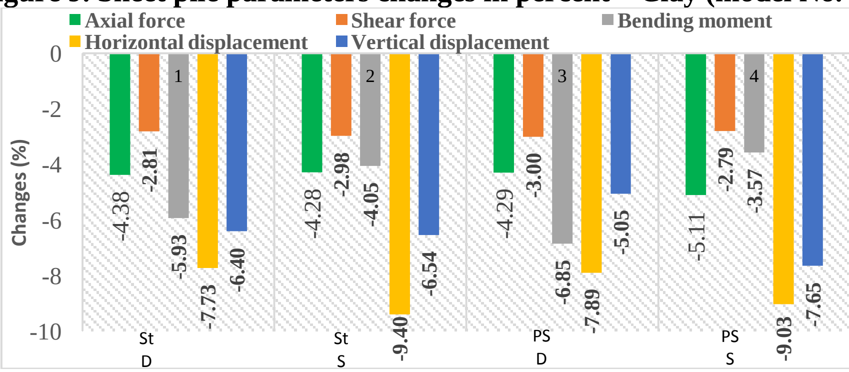

Figure 10. Sheet pile parameters changes in percent - Sand (model No.1)

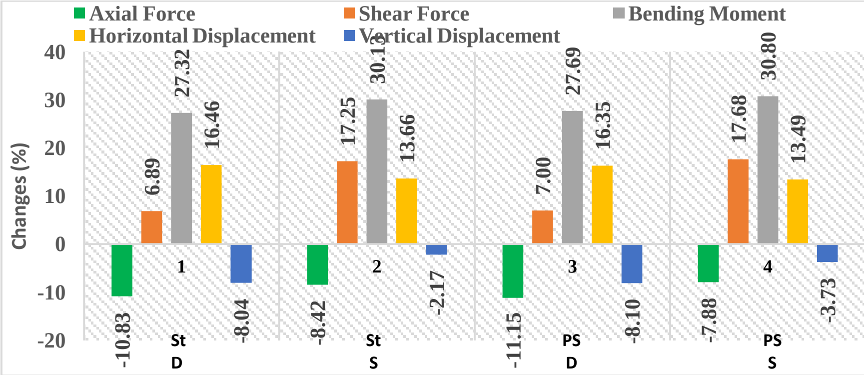

Figure 11. Sheet pile parameters changes in percent - Clay (model No. 2)

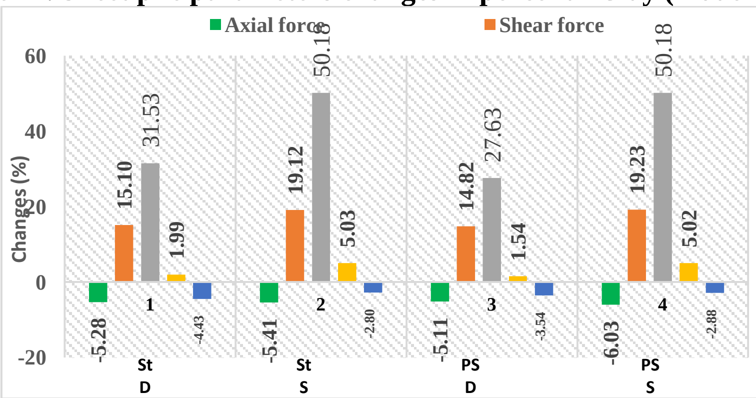

Figure 12. Sheet pile parameters changes in percent - Sand (model No.1)

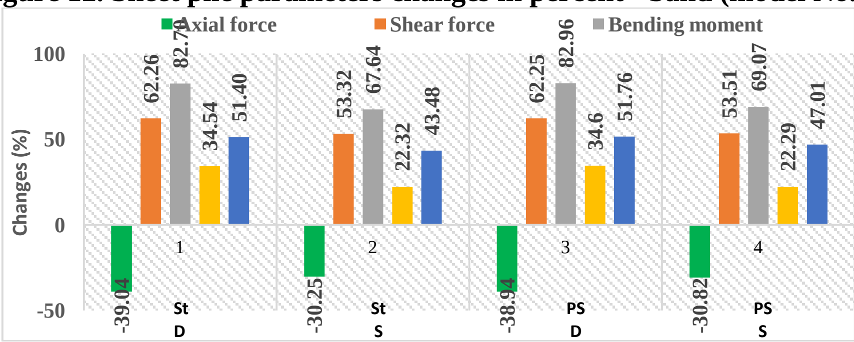

Figure 13. Sheet pile parameters changes in percent - Clay (model No. 3)

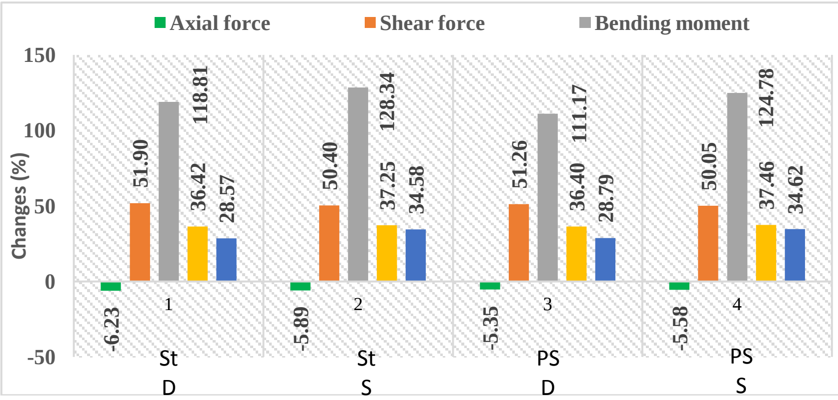

Figure 14. Sheet pile parameters changes in percent - Sand (model No.3)

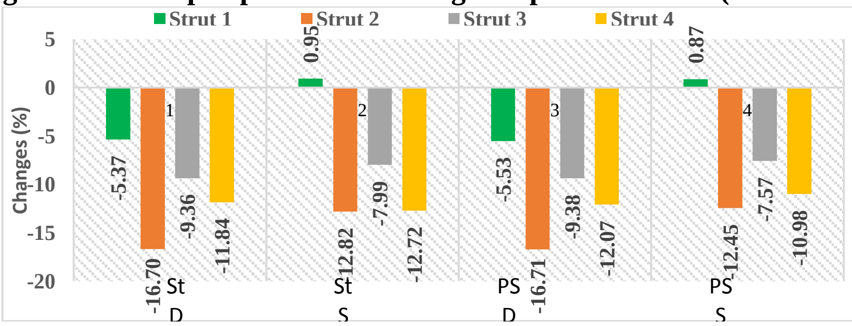

Figure 15. Strut forces changes in percent - Clay (model No.1)

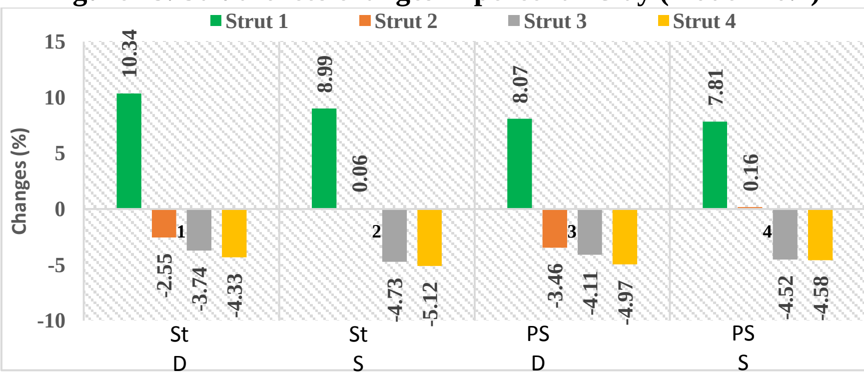

Figure 16. Strut forces changes in percent - Sand (model No.1)

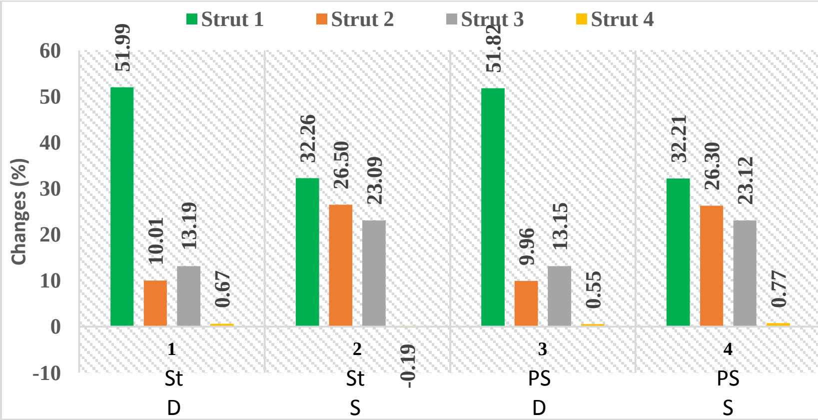

Figure 17. Strut forces changes in percent - Clay (model No. 2)

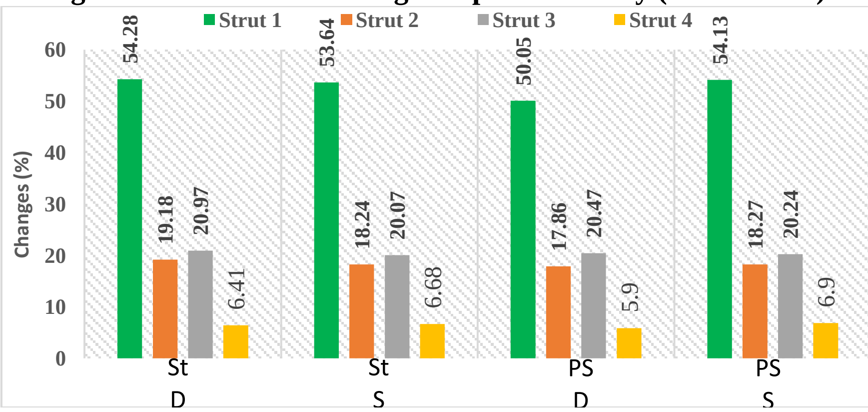

Figure 18. Strut forces changes in percent - Sand (model No. 2)

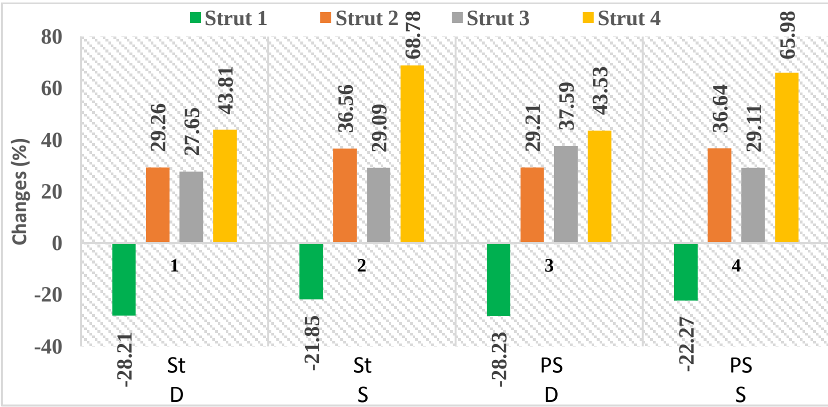

Figure 19. Strut forces changes in percent - Clay (model No. 3)

[DOR: 20.1001.1.22286837.1397.12.5.2.4]
[DOI: 10.18869/acadpub.jeg.12.5.31]

[DOI: 10.18869/acadpub.jeg.12.5.31]

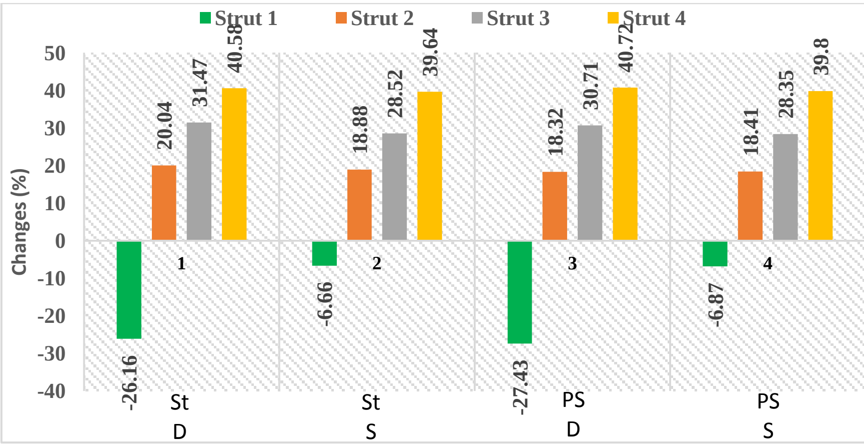

Figure 20. Strut forces changes in percent - Sand (model No. 3)

Discussion

Authors previous studies show that changes in soil total stresses are negligible and increasing loose layer's depth, decreases the total stresses changes. When loose clay layer exists beneath tow stiff clay layer, ground horizontal displacement increases more than 15%.

According to figures 9-14, sheet pile axial forces are decreased. It is shown that the changes in axial forces are less than (6~40) % in clayey models and (4~6) % in sandy models. In model No. 1 (top loose layer) shear forces and sheet piles bending moments decrease to 8.5% and 18% in clayey models, also 3% and 3.5~7% in sandy models. In clayey model No. 2 (middle loose layer) shear forces and bending moments increase about (6~18) % and (27~30) %, respectively, in comparison with model No. 4. In sandy model No. 2, shear forces and bending moments increase about (15~20) % and

(30~50) %, respectively, in comparison with model No. 4. In model No. 3 (bottom loose layer) sheet piles shear forces increase about (53~63) % in different conditions of clayey models and in sandy models increase about 50%. Bending moments of sheet piles increase about (22~35) % in clayey models and more than (110~125) % in sandy models depending on groundwater and analysis conditions.

Changes in vertical and horizontal displacements of sheet piles in model No. 1 are about 9% and 17% in clayey models and about (6~8) % and (8~9) % in sandy models. In clayey model No. 2, vertical displacements have slight changes in the saturated situation, but in dry situation change values are about 8%. Also, horizontal displacements changes are about (13~17) %. In sandy model No. 2 vertical and horizontal displacements have slight incremental changes, respectively. In model No. 3, horizontal displacements of sheet piles are increased significantly, about 35% in clayey models and about 37% in sandy models.

Normalized sheet piles lateral deformations are shown in Figures 21 and 22. It can be seen that normalized maximum lateral deformation values δ_{hmax} are between 0.05%H and 0.13%H in clayey models and between 0.022%H and 0.052%H in sandy models, where H is the excavation depth. The maximum value is related to model No. 3 about 0.13%H in clayey models and about 0.052%H in sandy models. Tables 3 and 4 represent the location of δ_{hmax} from ground surface in all models. This approximate location in model No. 2 is different from other models.

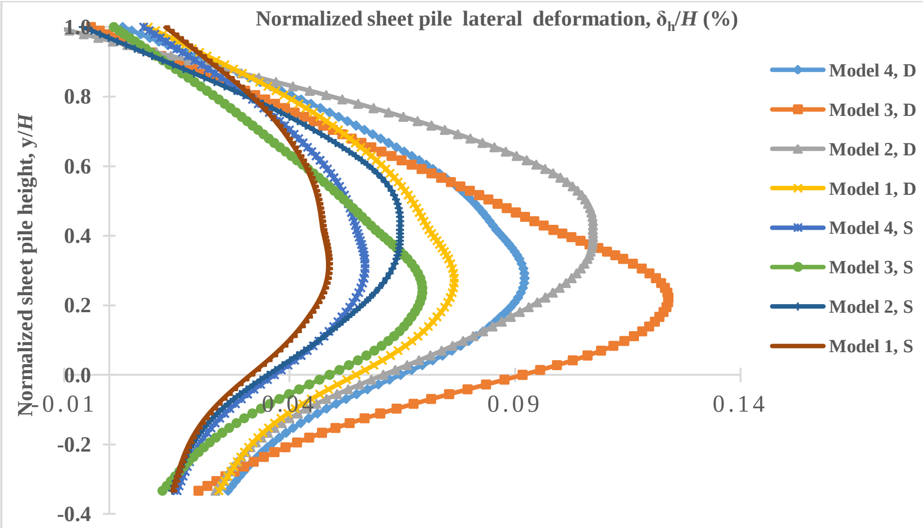

Figure 21. Normalized lateral deformation of sheet piles - Clay (static analysis)

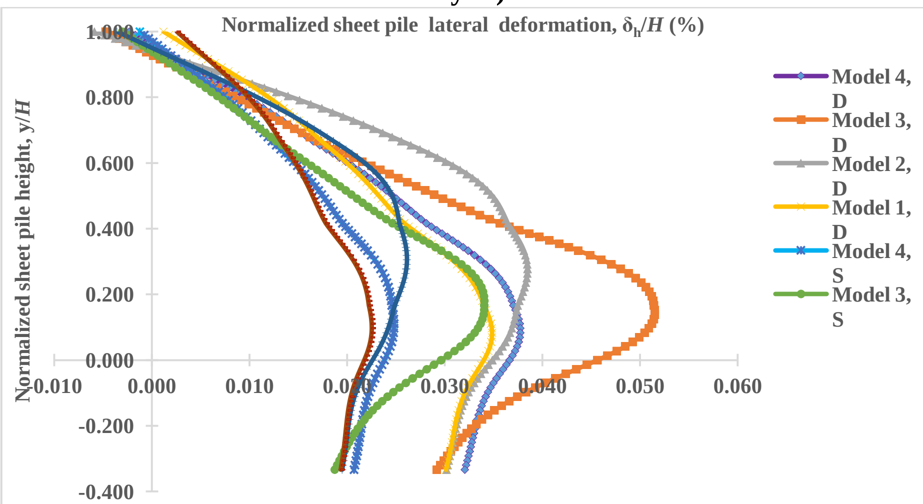

Figure 22. Normalized lateral deformation of sheet piles -Sand (static analysis)

Table 3. Location of maximum lateral deformation in clayey models

	Model No. 1	Model No. 2	Model No. 3	Model No. 4
Location of $\delta_{h\ max}$	0.72 H	0.55 H	0.78 H	0.71 H

Table 4. Location of maximum lateral deformation in sandy models

	Model No. 1	Model No. 2	Model No. 3	Model No. 4
Location of $\delta_{h\ max}$	0.92 H	0.7 H	0.85 H	0.9 H

The study performed by Long (2001) on database of some 300 case histories of wall and ground movements due to deep excavations, showed that for retaining walls in stiff soils, with a large factor of safety against excavation base heave, $\delta_{h\ max}$ are frequently between 0.05%H and 0.25%H, where H is the excavation depth. Also for retaining walls that retain a significant thickness of soft material (>0.6H), with stiff material at dredge level and where there is a large factor of safety against base heave, the δ_{hmax} values increase significantly from the stiff soil cases.

According to figures 15-20, when top loose layer exists, strut axial forces are decreased about (5~17) % in clayey models and (3~5) % in sandy models, except strut No. 1 that its force increased about (8~10) % in sandy models. In model No. 2 all strut forces are increased in this situation. Furthermore, Figures 19 and 20 show that loose layer existent under stiff layers increases strut forces in comparison with model No. 4, especially in middle struts. For example, in the sandy models, strut No. 3 force has increased more than 40% due to model No. 4.

Conclusion

In this research, effects of a single loose layer on the sheet piles behaviors, displacements, and stresses in an excavation are studied by finite element analysis. It should be added that possible uncertainties and errors in this work are based on data uncertainties, especially about parameters presented in tables 1 and 2.

According to the obtained results, it can be shortly conducted that:

1. Existence of a loose layer on two stiff layers that thicknesses of all three layers are same, generally has reducing effects on soil and sheet piles deformations, forces and bending moments of sheet piles. But these changes are negligible.
2. When a loose layer is located under stiff layers, shear forces acting on sheet pile wall are increased. As the loose layer depth increases, shear forces increase about 50%.
3. As the loose layer depth increases, lateral deformation and bending moments acting on steel sheet piles increase considerably. In the current study, it is shown that at a depth equal to two times of loose layer thickness, these parameters reach to their maximum values. In this condition, bending moments acting on sheet piles increased at least 70% in clayey models and 110% in sandy models in comparison with condition that all the soil profile consists of a homogenous stiff clay.
4. Existence of a loose layer beneath stiff layer generally increases axial forces of middle struts. It must be considered in the design of sheet pile wall system, especially in the design of middle struts and very important and substantial excavation projects.

[DOR: 20.1001.1.22286837.1397.12.5.2.4]
[DOI: 10.18869/acadpub.jeg.12.5.31]

5. Generally, with increasing depth and location of loose layer affecting parameters on sheet piles and struts behaviors have increasing tendencies.
6. Existence of a loose layer beneath stiff layer increases soil lateral movement. This issue is very important in the protection of adjacent buildings and public facilities during excavations.
7. Maximum lateral deformation of steel sheet pile wall from ground surface occurs in 0.89H in sand and 0.74H in clay. Existence of middle loose layer changes this location to 0.7H and 0.55H in sand and clay, respectively.

References

1. Ahmadpour B., Amel Sakhi M., Kamalian M., "Study of the Effects of Loose Clay Layer Existence on Sheet Piling Excavation Method", 2nd Iranian Conf. on Soil Mech. and Found. Eng., Qom, Iran, (October 2015) 14-15.
2. Ahmadpour B., Amel Sakhi, M., "Static and pseudo static study of loose clay layer effects on steel sheet pile walls behaviours", Bulletin of Earthquack Sci. and Engrg., 3(2), 87-100 (2016). (in Persian)
3. Athanasopoulos G., Vlachakis V., Pelekis P., "Installation and Performance of a Steel Sheet Pile Wall for Supporting an Excavation in Urban Environment", Geo-Frontiers (2011) 3370-3380.
4. Bilgin Ö., "Lateral Earth Pressure Coefficients for Anchored Sheet Pile Walls", International Journal of Geomechanics. 12(5) (2012) 584-595.

5. Bilgin Ö., Erten M., "Anchored Sheet Pile Walls Constructed on Sloping Ground", Contemporary Topics in Ground Modification Problem Soils and Geo-Support (2009) 145-152.

6. Das B. M., Sobhan Kh., "Principles of Geotechnical Engineering", Eighth Edition, CENGAGE Learning, Stamford, USA, (2013).

7. Finno R. J., Calvello M., "Supported Excavations: The Observational Method and Inverse Modeling", Journal of Geotech. and Geoenvir. Eng. 131(7) (2005) 826-836.

8. Gopal Madabhushi S., Chandrasekaran V., "Rotation of Cantilever Sheet Pile Walls", Journal of Geotech. and Geoenvir. Eng. 131(2) (2005) 202-212.

9. GuhaRay A., Baidya D., "Reliability-based analysis of cantilever sheet pile walls backfilled with different soil types using the finite-element approach", Int. J. Geomech., 15 (6) (2015).

10. Gurinsky M., "Long-Term Strength of Sheet Pile Bulkheads with Ground Anchors", Ports '01(2001) 1-8.

11. Hu Y., Liu G., Zhao Y., "Calculation Method of Deformation and Inner Force of a Sheet Pile Wall with Relieving Platform", ICTE 2013 (2013) 168-174.

12. Laefer D. F., Ceribasi S., Long J. H., Cording E. J., "Predicting RC frame response to excavation-induced settlement", Journal of Geotech. and Geoenvir. Eng. 135(11) (2009)1605-1619.

13. Lee S. H., Kim B. I., Han J. T., "Prediction of Penetration Rate of Sheet Pile Installed in Sand by Vibratory Pile Driver", KSCE Journal of Civil Eng. 16(3) (2012) 316-324.

14. Leonidou E. A., Athanasopoulos G. A., Pelekis P. C., "Deep supported excavation for the underground parking of the Hellenic Parliament: measured vs. predicted behaviour", Proceedings of the 15th Int. Conf. on Soil Mech. and Geotech. Eng. Instanblul, Turkey, Vol.2 (August 2001) 1493-1496.
15. Long M., "Database for retaining wall and ground movements due to deep excavations", Journal of Geotech and Geoenvir. Eng. 127 (3) (2001) 203-224.
16. Ma J., Berggren B., Stille H., Hintze S., "Deformation of Anchor-Sheet Pile Wall Retaining System at Deep Excavations in Soft Soils Overlying Bedrock", Deep and Underground Excavations (2010) 126-131.
17. Mana A. I., Clough G. W., "Prediction of movements for braced cuts in clay", J. Geotech. Engrg. Div., Vol. 107 (6) (1981) 759-777.
18. Moorman C., "Analysis of wall and ground movements due to deep excavations in soft soil based on a new worldwide database", Journal of Soils and Found. 44 (1) (2004) 87-98.
19. Ou C. Y., "Deep excavation, theory and practice", Taylor & Francis, London (2006).
20. Peck R. B. "Deep excavations and tunnelling in soft ground". Proc., 7th Int. Conf. on Soil Mech. and Found. Eng., State of the Art Volume, (1969) 225-290.
21. Ramsden M., Griffiths T., "Steel Sheet Pile Wall Wale Rehabilitation", Ports (2010)193-202.
22. Sahajda K., "Ground Anchor Loads Measured on an Excavation Sheet Pile Wall", Tunnelling and Underground Construction: (2014) 974-983.
23. Sellmeijer J., Cools J., Decker J., Post W., "Hydraulic Resistance of Steel Sheet Pile Joints", Journal of Geotech. Eng. 121 (2) (1995)105-110.

24. Shao Y., Macari E. J., "Information Feedback Analysis in Deep Excavations", International Journal of Geomechanics. 8 (1) (2008) 91-103.
25. Son M., Cording E. J., "Estimation of building damage due to excavation induced ground movements". Journal of Geotech. And Geoenvir. Eng. 131(2) (2005) 162-177.
26. Terzaghi K., Peck R. B., "Soil Mechanics in Engineering Practice", 3rd ed., John Wiley & Sons, Inc., New York, NY (1996).
27. USACE "Design of Pile Foundations", US Army Corps of Engineers Engineering Manual EM 1110-2-2906 (1991).
28. Underwood C., Greenlee R., "Steel Sheet Pile Used as Permanent Foundation and Retention Systems-Design and Construction", Earth Retention Conf 3(2010) 129-136.
29. Wong I. H., Poh T. Y., Chuah H. L. "Performance of Excavations for Depressed Expressway in Singapore", Journal of Geotech. And Geoenvir. Eng. 123(7) (1997) 617-625.
30. Yoo C. S. "Behavior of braced and anchored walls in soils overlying rock", Journal of Geotech. and Geoenvir. Eng. 127(3) (2001) 225-233.
31. Zekkos D. P., Athanasopoulos A. G., Athanasopoulos G. A. "Deep supported excavation in difficult ground conditions for the construction of a two-story underground parking garage in the city of Patras, Greece", Proceedings of Fifth Int. Conf on Case Histories in Geotech. Eng. New York, N.Y. (April, 2004).
32. Zdravkovic L., Potts D. M., St John H. D., "Modelling of a 3D excavation in finite element analysis", Geotechnique, 55 (7) (2005) 497-513.