Numerical Simulation of Cantilever Pile Wall (CPW) Supporting Excavations

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ABSTRACT

Cantilever Pile Walls (CPWs) are a fast and cost-effective solution for soil retaining structures, known for their sophisticated behavior. This paper investigates the effects of pile center-to-center spacing (S) and pile embedment length (Le) on soil surface settlement, pile bending moment, and wall lateral displacement. The study demonstrates that numerical simulations provide valuable insights into the behavior of CPWs. As Le decreases from 7 to 2.8, and the L/H ratio reduces from 2 to 1.4, the pile behaves more like a cantilever system, with a gradual loss of fixity. Additionally, increasing the surcharge load from 0 to 60 kPa results in a 172% increase in the predicted maximum bending moment of the pile. This numerical study enhances the understanding of CPW behavior under various loading conditions.

Keywords: *Cantilever Pile Wall, Numerical simulations, Bending moment, Lateral displacement, Soil surface settlement*

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1. INTRODUCTION

In the past decades along with the fast economic growth, most countries have endured extreme social reform with the construction industry playing a vital role. Due to the non-stop construction growth rate of high-rise buildings, basements need to go deeper and deeper. Additionally, for other underground works like subway construction, the soil must be retained as well.

Various soil retaining structures such as diaphragm walls, soil nailing system, bored pile wall, and sheet pile wall has been used for decades to support the excavations. Neglecting excessive lateral displacement of the retaining structure or progressive ground settlement would cause irrecoverable damage to the neighboring buildings. These two important parameters must be considered for designing temporary retaining systems.

Cantilever Pile Wall (CPW) as shown in Figure 1 is frequently used for retaining soil in gravelly soil sites and or sandy soil sites where the penetration of groundwater into the excavated area is not troublesome. The stability of such a wall relies upon the generation of earth pressure on both sides of the wall. The wall resists the overturning moment due to the earth pressure from the retain soil by developing a restraining moment due to the earth pressure along the embedded portion of the wall however the excavation depths are typically limited to about 4 and 5 m. Deeper excavations generally require wales and struts as lateral supports. Clearly, the construction efficiency would decline markedly for large area excavations. A key topic for designers is the question of how to increase the excavation depth (without a reduction in construction efficiency) by improving the stiffness of the cantilever pile wall to minimize deflection of the wall and settlement of the surrounding ground.

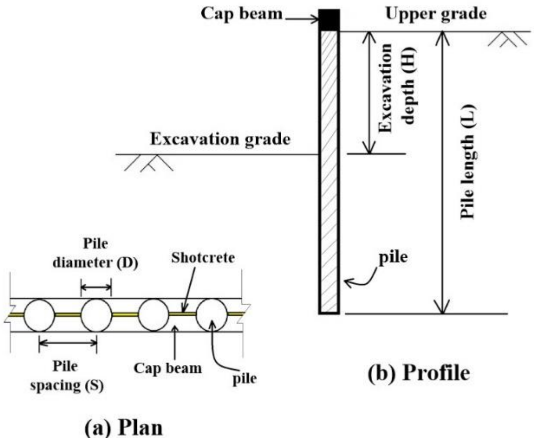

Fig. 1. *Cantilever Pile Wall (CPW)*

Cantilever Pile Wall (CPW) with shotcrete has been utilized extensively as an excavation retaining system. Some privileges of using a pile wall system are ease of installation, cost-effectiveness, and particularly suitable for restricted urban areas.

Researchers performed a series of geotechnical centrifuge tests to study the effect of lateral monotonic and cyclic loading on a short steel monopile. The effect of cyclic loading on the cyclic bending moment was discussed which resulted in the minor significance of that type of loading [1]. Experimental tests were conducted to determine the load-displacement mechanism of a stabilized earth wall where waste tires and uniaxial geogrids were employed as reinforcements [2]. They observed the vertical earth pressure on the wall increase with the increasing load applied at the top of the wall, as the wall horizontal displacement showed an increasing trend. Also utilizing reinforcements triggered a reduction in vertical earth pressure and horizontal displacement of the wall. They also proved that these kinds of reinforcements are desirable to be applied to a mechanically stabilized earth wall which is beneficial to the recycling of rubber resources and environmental protection. A similar approach was followed using sand-tire chips (STC) mixtures as backfill for a cantilever retaining wall (CRW) to alleviate and control the horizontal displacement and earth pressure on the structure [3]. They evaluated and analyzed the performance and stability of the CRW numerically using a finite element software, RS2. The results indicated that vertical and horizontal displacement, lateral pressure, maximum shear force, and bending moment were reduced when the retaining wall was fortified with STC instead of sand alone.

Researchers investigated the behavior of double anchored sheet pile wall system during excavation and tunnel construction [4]. The bending moment of the wall, top wall lateral, and vertical displacement of the piles were studied parametrically. They proved once the distance between anchors divided to wall height is 0.51 the minimum bottom wall bending moment will develop. Researchers used conventional analytical calculation methods based on subgrade reaction coefficient and by numerical method with Finite Element Method (FEM) to design a self-stabilizing retaining wall [5]. The goal of their research was to minimize the various uncertainties due to calculations and numerical modeling. In addition to using the Mohr-Coulomb soil model, Hardening Soil Model (HSM) was employed to investigate the variation of required and additional factors for the model as well as secant modulus stiffness.

Researchers assessed the behavior of a sheet pile wall in the vicinity of a strip footing through a series of experimental tests [6]. They proved that the most significant factor that influences the behavior of the sheet pile wall is the distance of the model footing so that the model footing would affect the sheet pile wall once it is placed within the Rankine wedge. Moreover, researchers simulated an anchored soldier pile wall for supporting excavation adjacent to buildings [7]. They employed Abaqus as a finite element method software to predict the displacement and internal forces of the retaining system especially due to surcharge. They also indicated that surcharge load had a great influence on the wall deformation and bending moment of the piles. Researchers used the finite element method interacting with a stochastic model to investigate the uncertainty of soil characteristics to determine the effects of the structural behavior of sheet pile wall [8]. The results indicated that friction angle was an important parameter and there were spatial variability parameters that could not be considered negligible.

Researchers proposed a detailed design methodology of an excavation supporting system and then compare this method to a case study on the contiguous bored pile wall system retained the excavation at the city center of India. Researchers studied the design approach of large diameter Cantilever Pile Wall (CPW) for a specific site in Hong Kong using the traditional model approach and the rational, safe, and economic approach explained in CIRIA regulation following monitoring of wall performance during and after construction [9]. Researchers conducted a series of centrifuge tests to assess the behavior of self-supported single and double soldier-piled wall in sandy soil under different loading conditions and pile arrangements [10]. The surface settlement, maximum horizontal displacement, maximum tilting angle, and maximum bending moment of the pile were reduced considerably due to adding another row of soldier-pile to the single one.

Construction of the Cantilever Pile Wall (CPW) first involves driving a row of piles around the excavation area. The distance between adjacent piles (S) is about 2, 3, or 4 times of pile diameter. A reinforced concrete cap beam is constructed to integrate the pile row into a frame wall system as shown in Figure 2. To mobilize the forces along with the pile, a portion of the pile is needed to be embedded in the soil as shown in Figure 2 which is called pile embedded length. In some critical situations, buildings may have existed on the top of excavation as a static loading which the allowable distance of building to the excavation tip must be taken into account.

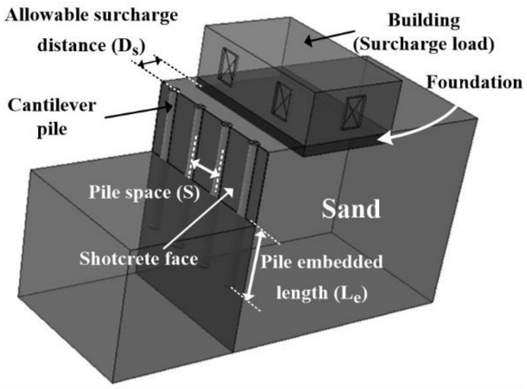

Fig. 2. *Excavation and building supported by CPW*

2. PROBLEM DEFINITION AND METHODOLOGY

The goal of this study is to evaluate the impact of key parameters on the design of CPWs for excavation support. The parameters under investigation include the pile center-to-center spacing (S) and pile embedment length (Le). Additionally, the effect of surcharge load, which simulates the weight of an existing structure, is considered. These parameters are crucial in assessing the performance of CPWs in supporting excavations and adjacent buildings.

Numerical simulations are employed to analyze the behavior of CPWs under various conditions. The findings from this study provide valuable insights into the design and optimization of CPWs, particularly in relation to their stiffness, deflection, and settlement control in urban excavation projects.

3. NUMERICAL MODELING

A numerical investigation using Finite Element Method (FEM) analysis software (Abaqus 3D, version 6.14) was implemented. Some of the applications of this software in geotechnical fields consist of simulating deep excavations, slope stability, and underground structures. The undeformed and deformed FEM mesh of simulated CPW supporting the excavation is indicated in Figure 3(a) and 3(b) respectively.

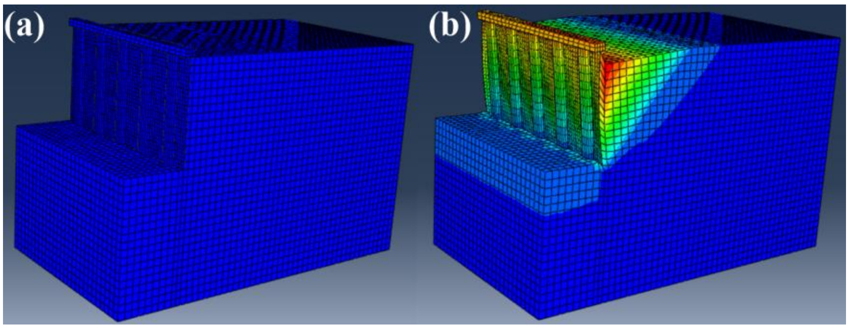

Fig. 3. *FEM mesh simulated for CPW protecting the excavation in Abaqus (a) undeformed mesh; (b) deformed mesh*

The prototype pile has a circular section with a diameter of 80 cm which is defining and shaping the meshes all around the pile length interacting with soil is so hard and time-consuming and leads to several plasticity divergences. Therefore, the section of the pile simulated in Abaqus was adopted as a square with a dimension of 70 cm. The equivalent section of the pile is obtained from equation 1 which defines the moment inertia of the circle and square section.

$$I_{circle} = I_{square} \quad \Rightarrow \quad \frac{\pi d^4}{64} = \frac{b^4}{12} \qquad (1)$$

The CPW was modeled in a 3D environment to retain the excavation in Abaqus. To simulate the stage construction, the total depth of excavation was 7 m which was divided into the first 2m, the second 2m, and the third 3m. To simulate the interaction between the soil and CPW, tangent and normal behavior was employed. Moreover, to join the shotcrete faces and capping beam to the piles, the embedded region and tie were used respectively as a constraint.

4. Results and discussion

*The properties which are going to discuss in this paper research are pile center to center spacing (*S*), pile embedded length (*Le*), and surcharge load at the tip of excavation (S_L). For the referred parameters, the lateral displacement of the wall, bending moment of the pile, and settlement of soil were obtained at end of the excavation.*

4.1. Role of pile center to center spacing (S)

Figures 4 to 6 indicate the importance of pile spacing on the pile bending moment, wall lateral displacement, and surface settlement, respectively. Figure 4 shows the variation of bending moment of pile versus the normalized pile length (pile length / (L/H)). The maximum bending moment of the pile occurs moderately lower than the excavation grade in every three graphs, which means that the concept of a cantilever structure system is fulfilled in retaining the soil. The piles provide the normalized spacing (S/D) of 2, 3, and 4 resulted in a maximum bending moment of $203\ kN.m$, $334\ kN.m$, *and* $434\ kN.m$ *in pile respectively. It means, once (S/D) decreases from 3 to 2 and 4 to 3, the shrinking rate of pile bending moment is 64% and 30%, respectively. Thus, the less center to center spacing applied to the piles, the lower the bending moment of pile measured. To explain this occurrence, once the spacing between the piles decreased, the CPW is getting stringer, so the number of piles which should withstand the lateral pressure from the soil (that causes the bending moment in pile) would be increased, consequently, each pile would share a minor bending moment.*

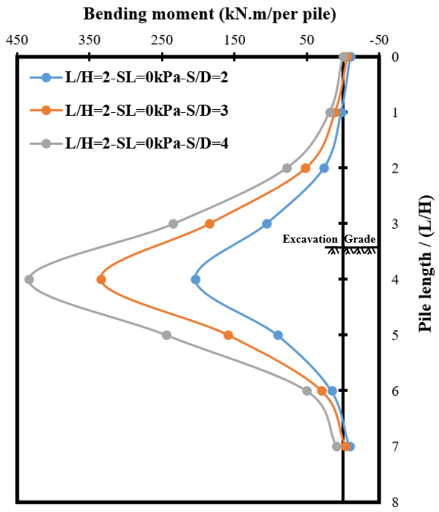

Fig. 4. *Effect of pile spacing on the variation of bending moment along the pile length*

It can be seen in Figure 5 that by increasing the pile spacing, the wall lateral displacement has increased. Maximum wall deflection was predicted at the top of the wall which this deflection was measured 4.63 cm for S/D=4 and 2.74 cm for S/D=2.

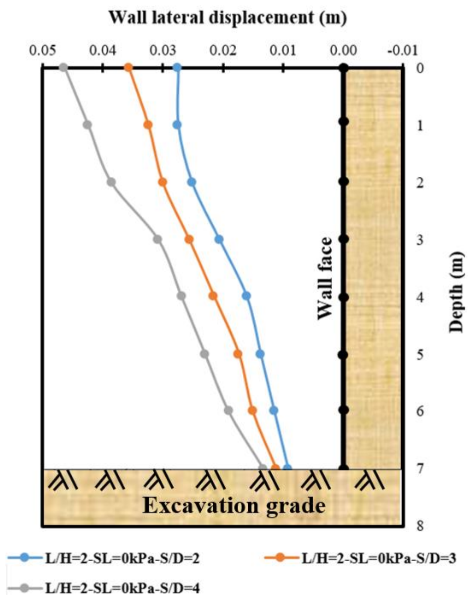

Fig. 5. *Effect of pile spacing on the variation of wall lateral displacement versus depth*

Figure 6 shows that the correlation between pile spacing and surface settlement. Increasing pile spacing causes a nonlinear propagation in the surface settlement. The insignificant phase of settlement happened at distance from the wall face of 8-14 m, but the substantial phase of settlement took place at 0-8 m which is almost equal to the depth of excavation. It means that the start point of settlement propagation strongly depends on the excavation depth. Maximum surface settlement is 4.1 cm, 2.58 cm, and 1.7 cm belong to S/D=4, S/D=3, and S/D=2, respectively.

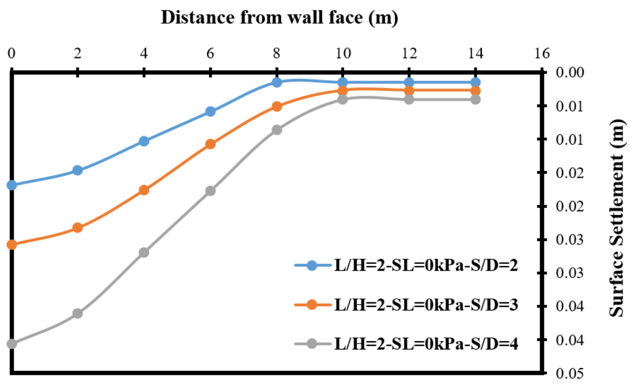

Fig. 6. *Effect of pile spacing on the variation of surface settlement versus distance from the wall face*

4.2. Role of pile embedded length (Le)

Pile embedded length is an effective parameter that plays a crucial role in designing the CPW system for retaining the excavation. Since the piles in CPW system do not anchor to the stable adjacent soil, their performance and design basis depend on the embedded length of the pile to fulfill the cantilever principle. Unlike the insignificant effect of pile spacing on wall deflection and surface settlement, the variation of pile embedded length (i.e., from 2.8 m to 7 m) shows the remarkable influence on the outputs. Figure 7 proves that the changes in pile bending moment graphs are not as uniform as those are indicated in Figure 4. The reason can be found in the pile embedment, which by decreasing the pile embedded length, the maximum bending moment of pile moves downward along the pile and the shape and trend of the graphs are changed. Since the embedded length of the pile is 7 m (L/H=2), the maximum bending moment was captured $434\ kN.m$ *at the length of 7.7 m (out of 14 m) of the pile. But when L/H decreases to 1.4 (Le=2.8m), the maximum bending moment of the pile was predicted* $376\ kN.m$ *at the length of 7.7 m (out of 9.8 m) of the pile. The result that can be drawn is that once Le decreased from 7 to 2.8 and simultaneously L/H decreased from 2 to 1.4 the pile works as a cantilever system, but the fixity gradually diminishes. As a result, the maximum bending moment of the pile slightly reduced and lateral displacement considerably rises that can be seen in the next figure.*

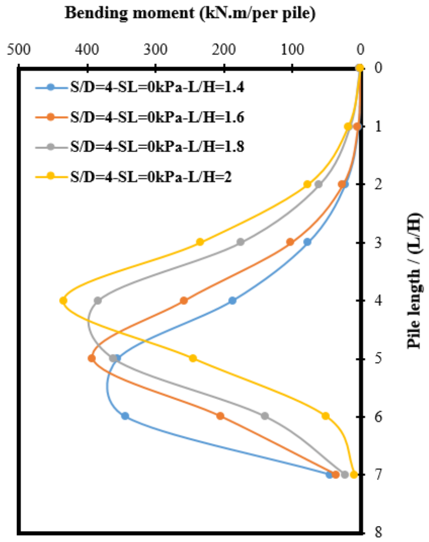

Fig. 7. *Effect of pile embedded length on the variation of bending moment along the pile length*

Figure 8 shows the variation of pile lateral displacement versus depth for various pile embedment. For embedded length of 7 m, 5.6 m, and 4.2 m, all resulted approximately in the maximum lateral wall *displacement of 4.63 cm. On the other hand, once the Le is 2.8 m (L/H=1.4), the wall deflection was increased progressively. A nonlinear variation in wall deflection was observed in the upper half of the graph corresponding to the L/H=1.4, led to a maximum lateral displacement of 19.2 cm which practically is a failure for CPW to retain the excavation.*

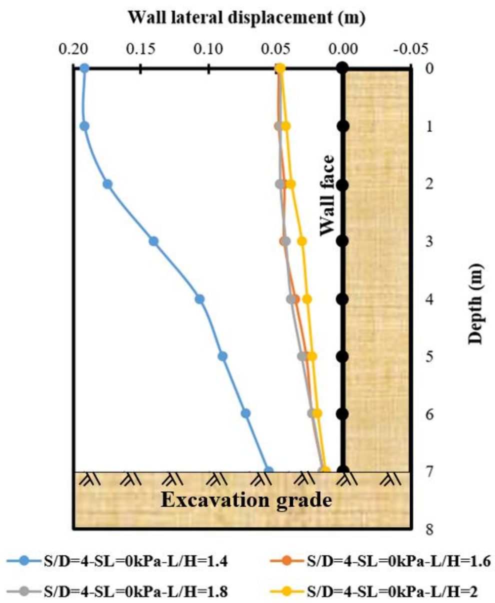

Fig. 8. *Effect of pile embedded length on the variation of wall lateral displacement versus depth*

A similar trend and behavior were observed for surface settlement once the embedded length of the pile was studied parametrically. Figure 9 indicates that CPW with L/H=2, 1.8, and 1.6, all resulted in a surface settlement of 4.06 cm. Once again, a nonlinear variation was noticed in the distance of 0-10 m which resulted in a surface settlement of 15.7 cm at the wall face. It is proven that choosing L/H=1.4 is not wise because it leads to excessive wall lateral displacement and surface settlement which resulted in failure in retaining the soil by CPW.

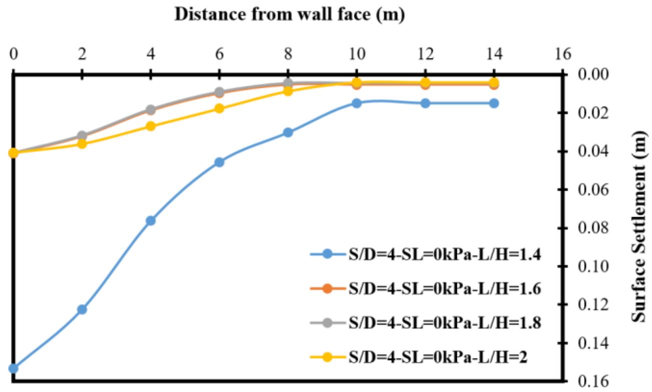

Fig. 9. *Effect of pile embedded length on the variation of surface settlement versus distance from the wall face*

4.3. Role of surcharge load (SL)

The predictions of the surcharge load influence on the behavior of CPW system are indicated in Figures 10 to 12. The width of (surcharge load) equivalent to foundation carrying the building at the tip of excavation is considered 7 m. Figure 10 illustrates the variation of bending moment of pile versus the normalized pile length (L/H). In every four graphs, the maximum bending moment of the pile occurs slightly lower than the excavation grade which means that the considered embedded length (L/H=2) provides the CPW with the cantilever structure condition. The excavation carrying the surcharge load of 0 kPa, 20 kPa, 40 kPa, and 60 kPa resulted in a maximum bending moment of 434 kN.m, 703 kN.m, 970 kN.m, and 1180 kN.m in pile, respectively. The bending moment at the tip and end of the pile in every four surcharge loading conditions is almost zero and ignorable. By increasing the surcharge load from 0 to 60 kPa, the predicted maximum bending moment in the pile would be increased about 62%, 124%, and 172%, respectively.

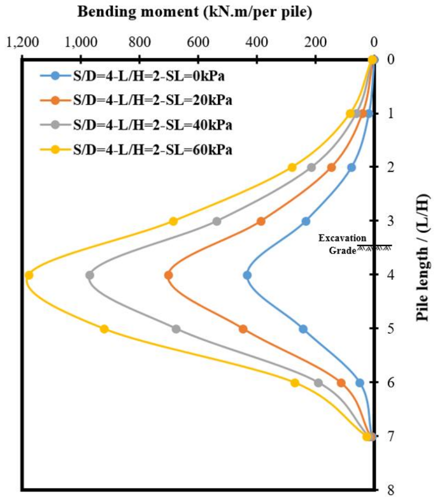

Fig. 10. *Effect of surcharge load on the variation of bending moment along the pile length*

Figure 11 indicates that for CPW supporting the excavation, the wall lateral displacement was exceeded along the wall face almost linearly in the four different analyses. For the surcharge load of 0 kPa, the wall lateral displacement changed between 1.3 cm and 4.6 cm, however, for 60 kPa surcharge load, it varied between 6.4 cm and 15.6 cm. Maximum wall lateral displacements increased by 339%.

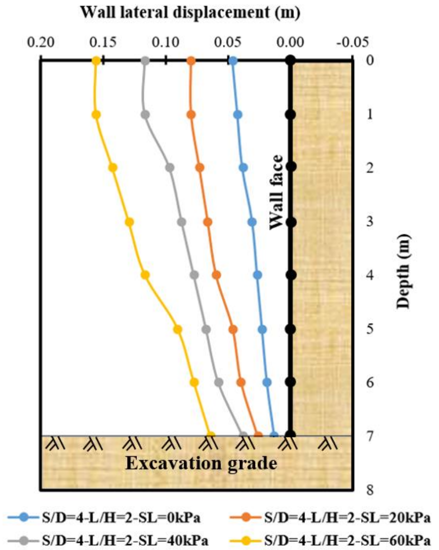

Fig. 11. *Effect surcharge load on the variation of wall lateral displacement versus depth*

The variation of surface settlement versus the distance from the wall face is indicated in Figure 12. Increase in the surcharge load from 0 kPa to 60 kPa leads to a remarkable propagation in the soil surface settlement for a distance of 10 m from the wall tip. The range of surface settlement variation without *surcharge is from 0.3 cm to 4.1 cm. For the surcharge load of 60 kPa, the range of settlement variation is from 1.63 cm to 14.8 cm. The point is that by increasing the surcharge load, extreme propagation was observed in soil surface settlement, in which maximum settlement has increased 361%. In such excavations must be controlled the settlement. This may require considering some distance of surcharge load from the wall tip.*

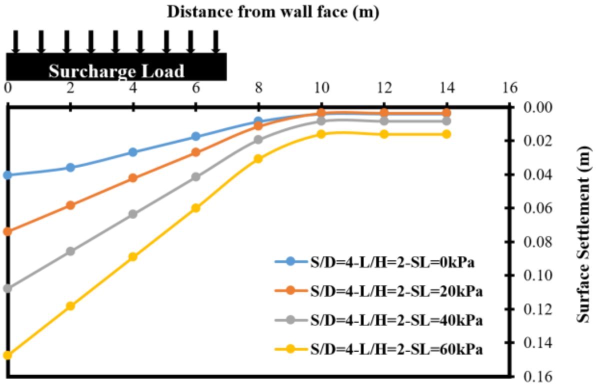

Fig. 12. *Effect of surcharge load on the variation of surface settlement versus distance from the wall face*

5. Conclusion

The major goal of this paper was to assess the determinative parameters which play an important role in Cantilever Pile Wall (CPW) behavior. Nine experimental tests were conducted to investigate the influence of pile center to center spacing and compare their results to those predicted from numerical analysis. In addition, various numerical simulations were carried out to have a better understanding of the CPW behavior. The following main conclusions are obtained.

1. *Pile embedded length is the key parameter for designing the CPW to retain the structure properly. Since there is no anchorage for piles into the adjacent soil, it is very important to provide the pile with the concept of a cantilever system. It was proven that when L/H=2 and L/H=1.8 this concept is fulfilled, and wall lateral displacement and surface settlement were under control. In addition, once the piles are cantilever enough to resist the soil pressure, the expected maximum bending moment of the pile was predicted a little lower than the excavation grade.*
2. *Decreasing pile center to center spacing would affect the bending moment of the pile considerably, but variation in pile spacing does not trigger the wall deflection and surface settlement that much. Consequently, pile spacing is not a very crucial parameter in controlling the wall deflection and surface settlement.*
3. *A major part of the soil surface which is affected by the settlement is almost 0-10 m from the wall face. This range directly depends on the excavation depth.*
4. *The larger the surcharge, the higher the bending moment of the pile was measured. This is due to more normal stress being transferred to the piles (according to the lateral coefficient of earth pressure, k), withstanding the lateral pressure. Furthermore, increasing in surcharge load led to excessive propagation in wall lateral movement and surface settlement which it is suggested to consider an allowable distance for excavation crest from the adjacent buildings.*
5. *Furthermore, once Le decreased from 7 to 2.8 and simultaneously L/H decreased from 2 to 1.4 the pile works as a cantilever system, but the fixity gradually diminishes. Moreover, by increasing the surcharge load from 0 to 60 kPa, the predicted maximum bending moment in the pile would be increased about 172%.*

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