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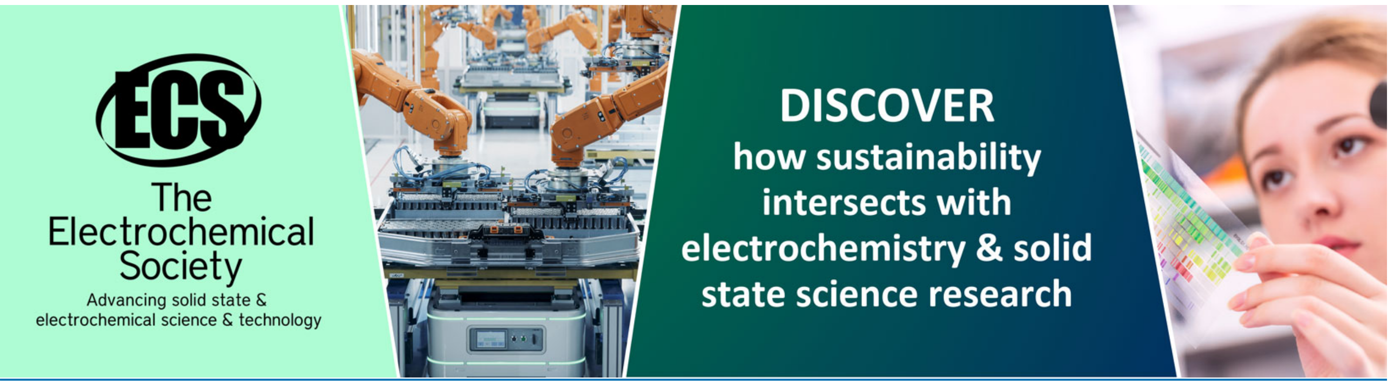

Effect of Groundwater Table Rising and Slurry Reduction during Diaphragm Wall Trenching on Stability of Adjacent Piles

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Abstract. The process of diaphragm wall trenching normally affects the surrounding environment. The piles near a diaphragm wall trench are commonly affected by the trenching process as well. During trenching the slurry level and the natural groundwater level are assumed to be constant. However flooding may cause damage to the slurry trenches due to the increase of the groundwater table. Another possible scenario for the trench failure is due to reduction of the slurry level. The reduction of the slurry level could be due to the presence of cavities or a very coarse soil layer. Piles located near a trench could be affected greatly if the trench is subjected to reduction of slurry or increase of the groundwater level. This research focuses on studying numerically the stability of piles adjacent to the diaphragm wall during the trenching process, especially in cause of slurry reduction or increase of groundwater level. The slurry reduction were simulated numerically with the finite different analysis and compared with previous laboratory work. The increase of groundwater level is simulated for a case study in Giza, Egypt. Groundwater level was assumed to increase in the area. Piles are generally affected by the trenching process. The behaviour of the pile is related to its position from the slurry trench. The stability of the pile may not be affected greatly by a normal and successful trenching process. However slurry reduction or increase in the groundwater level may cause a great effect on the stability of the nearby piles. Trenching in general causes an increase in pile settlement, horizontal displacement and bending moment. The pile skin friction and end bearing are affected as well. The percentage of the change in slurry or groundwater levels affects piles deflection and bending moment.
Key words: slurry trenches; pile; finite difference; finite element; skin friction; end bearing; diaphragm wall.

1. Introduction

The use of diaphragm walls inside cities is now very common. Such walls could be located near a deep foundation, especially in the crowded modern cities. During trenching, the soil near the trench is expected to be deformed. The settlement due to trenching was previously discussed and summarised by [1] . The same study was made by [2] for several metro stations in Cairo. The settlement equation due to trenching was then derived. [3],[4], [5] and [6] studied the deformation due to diaphragm wall trenching including the trenching effect on lateral earth pressure coefficient. From such findings, the soil deformation due to diaphragm

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wall trenching is in most cases relatively small and its effect on the surrounding structures is limited. However, a collapse during trenching of a diaphragm wall due to flooding and water table rising was observed and discussed by [7]. [8] Investigated the collapse of two slurry trench panels in underground metro station due to heavy rainfall that caused groundwater rising.

Drop in slurry level is also possible if the slurry penetrated into the soil. The study conducted by [9] on the filter cake showed that if the soil is very coarse, the penetration of slurry into such soil is expected and could be a reason for reducing the slurry level. Additionally the slurry level should be 1.5m higher than the groundwater level [10]. [11] Performed a field test to study the effect of trenching on adjacent piles in mixed soil layers. It was found that piles were deflected due to trenching; however the settlement of piles and soil was the same so that the bearing capacity of piles didn't show noticeable change. [12] and [13] performed a parametric study using centrifuge tests to investigate the effect of slurry trenching panels on adjacent single pile. The slurry reduction effect was the purpose of such models. A case study for slurry trenching and deep excavation near a deep foundation was investigated by [14] and [15]; the ground surface settlement due to trenching was the main investigation issues.

The collapse shape of the trench is expected to be the key rule influencing the nearby piles. If the failure of the slurry wall is in the upper part it may cause a horizontal upper movement on the pile equivalent to an additional horizontal upper load on pile. On other hand, if the trench collapses in the lower level it will probably causes maximum horizontal movement of the pile but not at its top. Piles are expected to moved together with the surrounding soil [16].

Studying the effect of trench collapse due to slurry reduction or rise of groundwater table on the piled foundation is the purpose of this paper. A comparison was conducted between the numerical simulation and the centrifuge model test results presented by [12]. On the light of such comparison a wider numerical parametric study was conducted to investigate the effect of slurry reduction and groundwater rising on the adjacent pile foundation. In addition the effect of reduced slurry pressure at some levels was also included in such study.

2. Centrifuge Model Tests and Remarks

Centrifuge model tests were conducted by [12] to investigate the effect of trenching on single pile in dry sand (no groundwater table). Reducing the slurry in a trench was investigated instead of investigating the effect of high groundwater table on the shallow trench instability. There were eight successful centrifuge tests made in such work.

2.1. Test discretion

The sand density and friction angle were 32^o and 15.55 kN/m^3. It was placed in a strong box of dimension 700mm x 400mm x 470mm to depth of 400mm equivalent to 30m. The pile in the tests was simulated using aluminium pipe with outer diameter of 12mm (0.9 m in real scale). The pile had to penetrate about 10mm in the soil to reach a final depth of about 250 mm equivalent to 18.5m. The trench depth and thickness were 350mm (26.25m) and 16mm (1.2m) in all tests; however the length was 40mm (3m) and 80mm (6m). The guide wall was also simulated. The average slurry density was 10.97kN/m^3. The pile was chosen to be at offset distance of 3.5D, 5.6D and 7.7D where D is the pile diameter.

2.2. Test procedures

After placing the sand in the strong box, the trench was filled with water. Latex membrane was used to prevent penetration of water to the sand. Pile penetrated then into the sand and the load used for penetration was released keeping a normal load on the pile. The water was replaced with liquid equivalent to the slurry. Finally reduction for the slurry was made.

2.3. Remarks about the test

The absence of groundwater table is not common in most of the soil conditions. Using the water inside the trench in the initial condition affected the real initial state. The water inside a trench provides horizontal pressure of $\gamma_w z$ (9.8z), while the soil pressure should equal to $k_o \gamma_s z$ (7.3z). In this case horizontal displacement had occurred in the soil direction.

Two dimensions stability analysis suggested by [7] could be used to find out the minimum slurry depth that keeps the trench stable. The factor of safety could be calculated from equation 1.

$$FS = P_s / P_f. \quad (1)$$

The slurry force Ps calculated as

$$Ps = \gamma_s Z_s^2/2 \quad (2)$$

γ_s and Z_s are the slurry density and depth, respectively. The horizontal acting force is calculated from equation 3.

$$P_f = [\gamma Z^2/2(\sin\theta - \cos\theta \tan\phi) + U \tan \phi]/ (\cos\theta + \sin \theta \tan \phi) \quad (3)$$

γ is the soil density and Z is the trench depth. The value of θ (the inclination of the plane of failure) was used as $45^o + \phi/2$. As the water pressure U is equal to zero and friction angle ϕ equal 32^o the horizontal acting force P_f equal 62.7kN/m`. In this case the slurry level could be only 3.5m (87% reduction in slurry) to achieve a factor of safety equal unity. However, this solution considered conservative one as it ignores the arching effect around trench ends. The comparison made by [17]showed that [7] two dimensional method provides the lowest factor of safety value. Accordingly, three dimension analytical solution by [18] for such case provides a factor of safety equal 1.35 for the 6m length trench and 2.35 for the 3m length trench.

From the above the trench could sustain global failure if the slurry reduced up to about 90%. The horizontal movement of the trench face could in this case govern the stability of the trench. However, the above equations didn't deal with the local failure. In realty filter cake is formed during trenching but indeed it is not strong enough to form a structural membrane; it only prevents grains' penetration inside the trench [19]. In contrast, [9] showed that filter cake is important for the stability in the case of sand, as the filter cake permits a full slurry pressure and it could also prevent local failure.

The slurry in the tested trench was reduced up to about 60% for the long trench and 80% for the shorter one. The used latex membrane should have played the role of the filter cake but indeed it could provide some additional strength for the trench wall surface. It is possible that the pattern of soil deformation was affected by the presence of such membrane. The detected failure in the experiment was due to large deformations that could damage the model pile. However, the tests provide a very good overview of the effect of trenching on piles. Therefore, numerical analyses were used to simulate such tests with the proper approximation in order to point out the reliability of the numerical models.

3. Numerical Simulation for the Tests

Table 1 shows a small description of each test. The numerical simulation of the tests was made using commercial software FLAC3D® which based on Finite difference analysis. The numerical simulation of tests CKC3, CKC6 and CKC16 was similar. Accordingly, a total of 6 numerical models were made for such simulation and comparison.

Table 1. Summary of successful centrifuge tests.

Test	*Panel length (m)*	Pile offset distance (m)	Number of Concrete panels	*Slurry density (kN/m³)*	*segmental pile resonse*
CKC1	6.0	6.93	-	10.97	N/A
CKC3	6.0	3.15	-	10.95	N/A
CKC6	6.0	3.15	-	10.89	N/A
CKC7	6.0	5.04	-	10.92	N/A
CKC13	3.0	3.15	1	10.92	A
CKC14	3.0	3.15	2	10.91	A
CKC15	3.0	3.15	-	10.92	A
CKC16	6.0	3.15	-	10.93	A

Note :The dimension is in the prototype scale

3.1. Modeling of soil

The soil was modelled using strain hardening softening soil model. The used friction angle was 32^{o}; the sand density was 15.55kN/m^3. The strain hardening softening soil model used in FLAC required relation between mobilized friction angle and plastic strain which can be calculated according to (Byrne, 2003) as:

$$\varepsilon_p = \frac{P_{ref}}{\beta G^e_{ref}} \times \frac{sin\emptyset}{R_f}\left((1 - \frac{sin\emptyset_m}{sin\emptyset} R_f)^{-1} - 1\right) \& G^e_{ref} = \frac{E^{ref}_{ur}}{2(1+\vartheta_{ur})} \quad (4)$$

Where ϕ_m is the mobilized friction angle, ϕ is the ultimate friction angle, ε_p is plastic strain, ε_f is the strain needed to mobilize the limit friction angle, P_{ref} is the reference pressure, R_f is the failure ratio, β is calibration factor, G^e_{ref} elastic tangent shear modulus and ϑ_{ur} is the undrained poisons ratio.

3.2. Modeling of guide wall, pile and latex membrane

The guide wall was modelled as an elastic soil element in order to simulate the1.5mm (11.5cm – prototype scale) thick aluminium steel plate. The chosen properties for such element were equivalent to the used aluminium material.

The implemented Pile element in FLAC was used to model the pile. Material and coupling spring properties were used to define such model. The pile was solved with stiffness matrix which divided it into finite elements. Between the pile and soil grid frictional and normal interaction accrued. The shear and normal coupling stiffness were defined according to equation 2 provided by FLAC manual [21]. The friction angle for the spring was chosen according to the values of the mobilized interface friction angle [12].

The latex membrane was modelled using the shell element. The thickness of the shell element was chosen to be 10cm with a small value of deformation modulus. The used shell element was mainly to prevent the local failure as the latex membrane was probably functioned.

3.3. Numerical Construction Stages

The numerical stages of construction were chosen to simulate each laboratory test. All the tests were used to simulate a single panel except two tests. These two tests were used to simulate multiple panels including concrete panels. The general simulation process is placing the sand in the strong box. Theoretically, the pile should be placed before the diaphragm wall. However, the water was placed first inside the latex membrane to keep the position of the diaphragm wall. The pile installation took place after water filled the latex membrane. A load was applied to make the pile penetrates 10mm inside the sand and then the load was removed. The water inside the trench was replaced with liquid which represent the slurry. Finally, the

slurry is to be reduced in stages until noticeable failure occurred. Slurry is to be replaced by concrete if a multiple panel is to be simulated. More details about the test could be found in [12] and [13].
The numerical simulation phases were chosen to simulate the centrifuge tests. The guide wall was initially simulated by replacing soil properties with concrete properties at its location. Soil elements in the trench position were removed in stages of 5m approximately. Water pressure is simultaneously applied on the trench wall. Pile penetrated after that in the soil to approximately 75cm. The water pressure is then replaced by the slurry pressure of 10.97kN/m^2. The pressure is then removed gradually to simulate the slurry reduction process. The concrete panels were simulated by reactivating the soil in such location and replace its properties by concrete properties. General geometry, construction stages and typical mesh model is shown in Figure1.

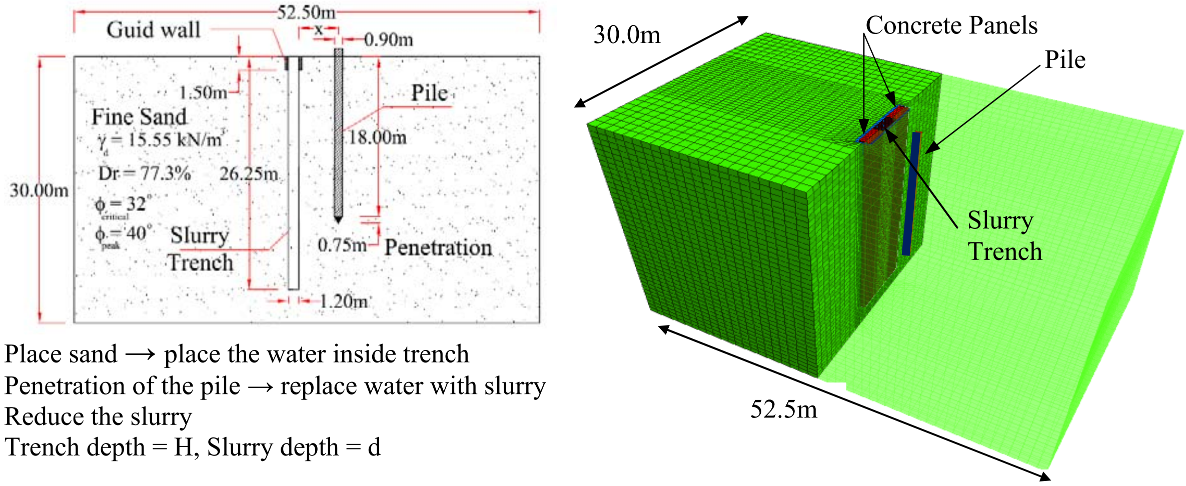


Figure 1. General geometry, construction stages and typical mesh used for simulation.

4. Results and comparison

This section discussed and compared results from finite different analysis and centrifuge model tests. Soil settlement and pile behaviour in different construction stages are the focus of the comparison.

4.1. Results relating to soil settlement

The comparison between centrifuge tests and Finite difference results regarding settlement of soil due to pile installation and slurry reduction are presented in this section. The settlement due to pile installation is shown in Figure 2. The settlement from the numerical analysis and from the test was in a good match. Figures 3, 4 and 5 show the settlement due to slurry reduction. Generally, the settlement due to slurry reduction from numerical analysis was quit in a good contrast with laboratory work. However, the settlement from the numerical analysis was decreased with distance shorter than that from laboratory tests. The shape of settlement from numerical analysis was in better contrast with [1]. The settlement for the 3.0m length trench was much lower than the trench with 6.0m length; this indicates that the length of the trench have a great effect on soil settlement.

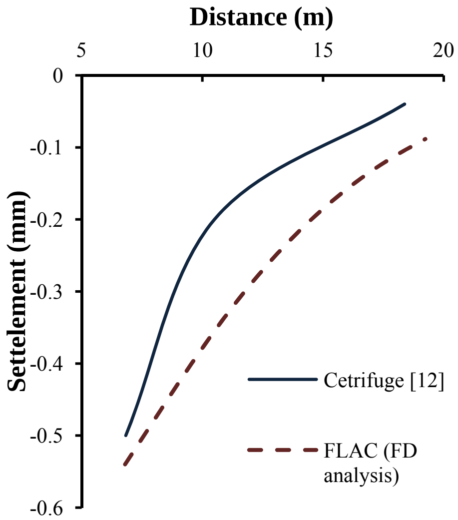


Figure 2. Typical Settlement due to pile installation.

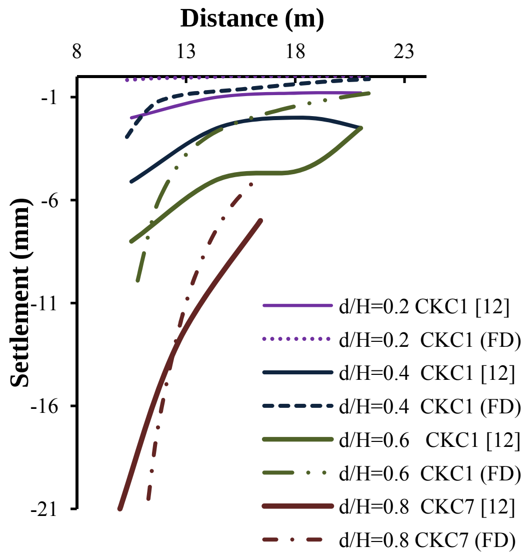


Figure 3. Settlement due to Slurry reduction (CKC1 and 7).

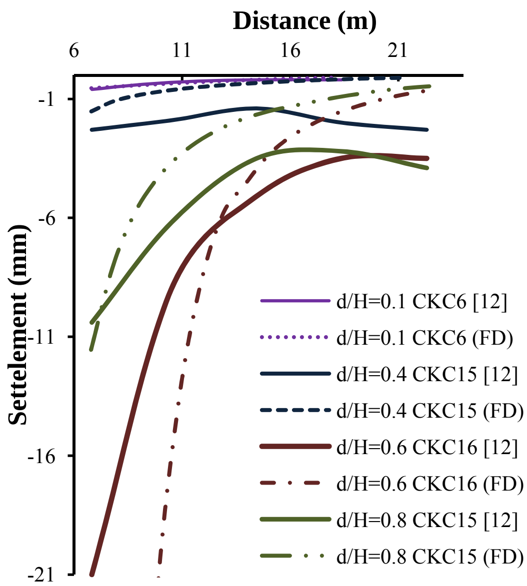


Figure 4. Settlement due to Slurry reduction (CKC 6, 15 & 16).

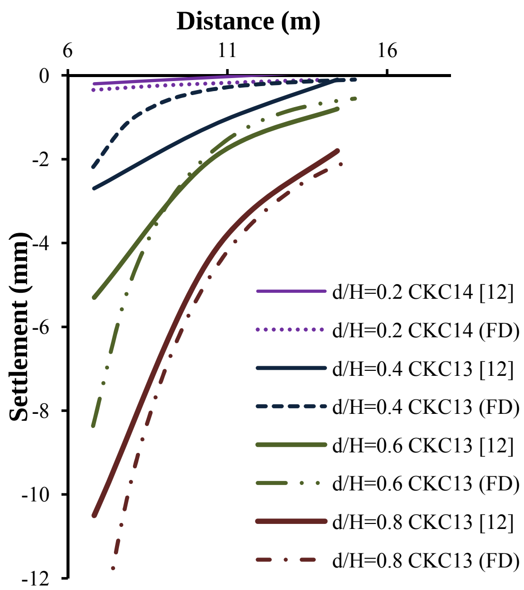
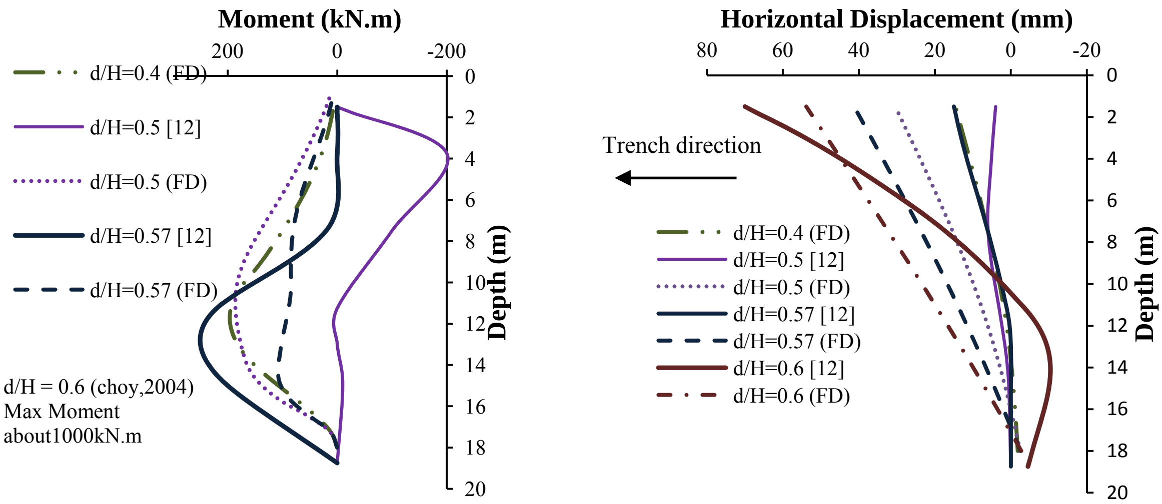


Figure 5. Settlement due to Slurry reduction (CKC 13 & 14).

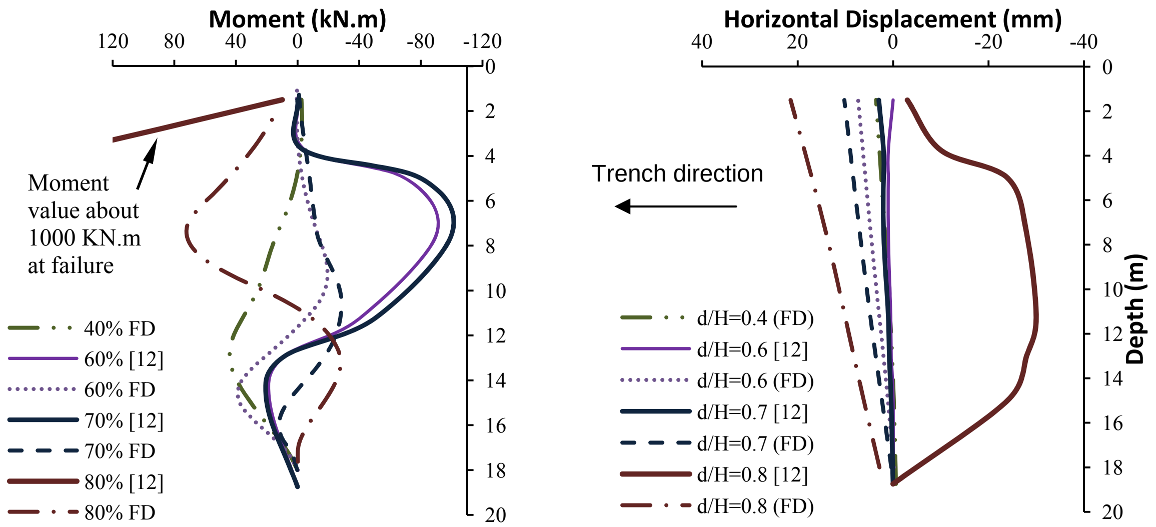
4.2. Results of pile horizontal movement and bending moment

The horizontal displacement and bending moment of piles due to slurry reduction from numerical and laboratory tests are presented and compared in this section. It can be obvious from Figures 6 and 7 that horizontal displacement and bending moment from FLAC analysis and laboratory experiments have almost the same shape; however, the values are different. The values of the laboratory tests were probably affected by eccentric loading which have probably caused a disturbance in the horizontal displacement and bending moment values of the pile. The direction of horizontal displacement in CKC 15 for the last stage was illogical as the displacement was moving against the wall. Generally, the values of bending moment at failure were relatively high compared to the numerical analysis.



Bending Moment Horizontal displacement

Figure 6. Pile horizontal displacement and Bending Moment due to slurry reduction (CKC16).



Bending Moment Horizontal displacement

Figure 7. Pile horizontal displacement and Bending Moment due to slurry reduction (CKC15).

4.3. Results of pile shear force and base load

The shaft frictions during slurry trenching are presented in Figures 8 and 9.The values from the laboratory tests and the numerical analysis show that shaft friction increases with slurry reduction. The last stage of construction shows a higher difference between the laboratory results and the numerical analysis. The collapse that happened in the laboratory experiment and didn't happen in the numerical analysis is the reason behind that noticeable difference. However, the trend of force is almost identical. The bearing capacity of pile decreased with slurry reduction. The percentage of decreasing predicted from the laboratory and numerical analysis was almost identical. The values of bearing capacity doesn't show noticeable change until the slurry reduced to about 40% (10.5m). According to [12], the skin friction increased due to the decrease of bearing capacity.

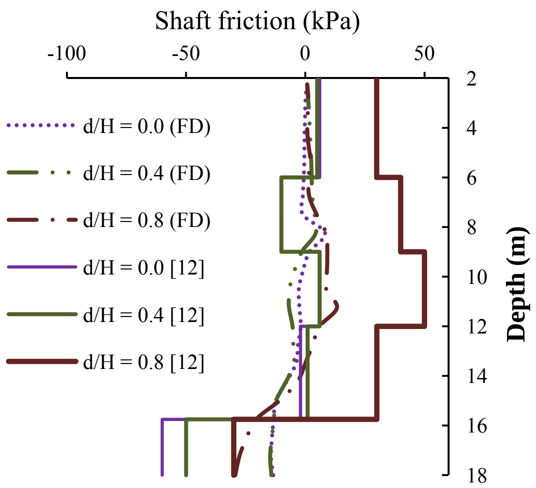


Figure 8. Pile shaft friction during slurry reduction (CKC 15).

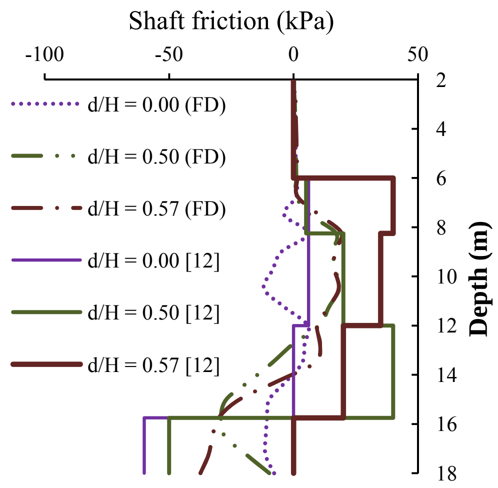


Figure 9. Pile shaft friction during slurry reduction (CKC 16).

5. Assumption of rising water table in a case study

A case study in Giza, Egypt is discussed in this section. The case study is described in details by Abdel-Rahman& El-Sayed (2002, 2009). It was a deep excavation constructed near piled foundation. The settlement due to diaphragm wall trenching was measured and simulated in the normal case. In this research, a model is made to simulate the same case with raising the water table. The effect of such rise on the ground settlement and pile behaviour is to be discussed and compared with the normal case. The soil was mainly sand with density ranging between 17.0 and 20.0kN/m^3. The friction angle varies between 28^o and 36^o. The upper soil layers were Fill and silty Sand while the lower soil layers were medium dense and dense Sand.

5.1. Modeling the case history

A 3D finite element Analysis (PLAXIS 3D®) was used in simulating the case history. The water level in normal condition was 2.0m below the ground surface and it was simulated that it rises up to the ground level as in the flood case. During trenching process of the last panel, the water table is assumed to increase and reach the ground surface. The other panels in this case were already filled with concrete. Figure 10 discussed the used mesh model.

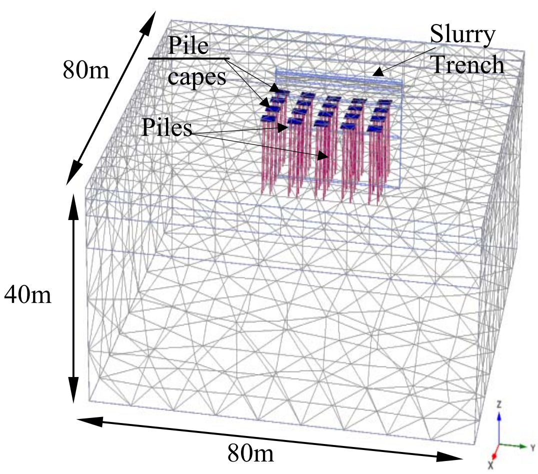


Figure 10. Mesh used in modelling the soil layers is 15-node triangular element with 15 Gaussian points. Hardening soil model used to model the soil layers while Elastic soil model was used to simulate the concrete panels. The piles were simulated using embedded pile element. Plate elements were used to simulate pile caps. The building load was distributed on the pile caps.

5.2. Settlement comparison and pile numerical results

The plane showing sections and panels is presented in Figure 11. All panels were assumed to be filled with concrete except panel P-20. Settlement of soil due to trenching and water rising from finite element and field data are presented in Figure 12. Soil generally heaved due to water rising; on the other hand piles 1, 2 nearest to the excavated panel P-20 showed a noticeable horizontal movement during water rising as shown in Figure 13. The shape of bending moment was also affected with water rising. The bearing capacity was almost constant; however, skin friction decreased for pile 1 and pile 2 to values about 45% and 25%, respectively. This reduction was significant and may cause failure to the pile. The reduction in skin friction was due to the decrease of the earth pressure coefficient. The skin friction didn't increase as in the previous section because the end bearing was not changed.

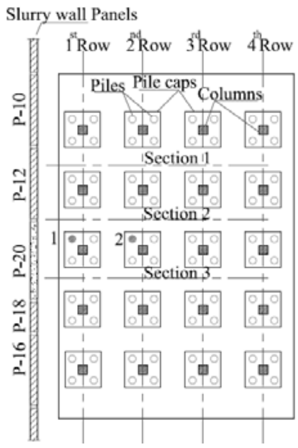


Figure 11. Piles and slurry trench

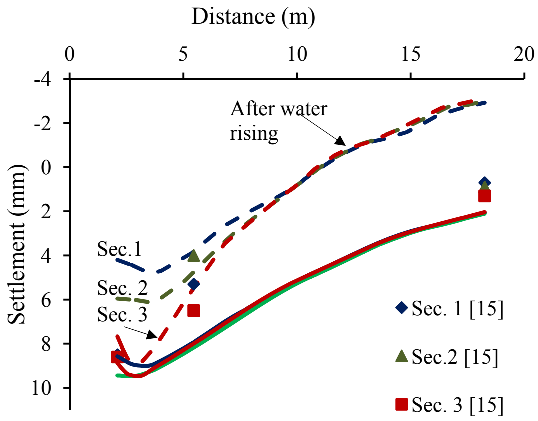
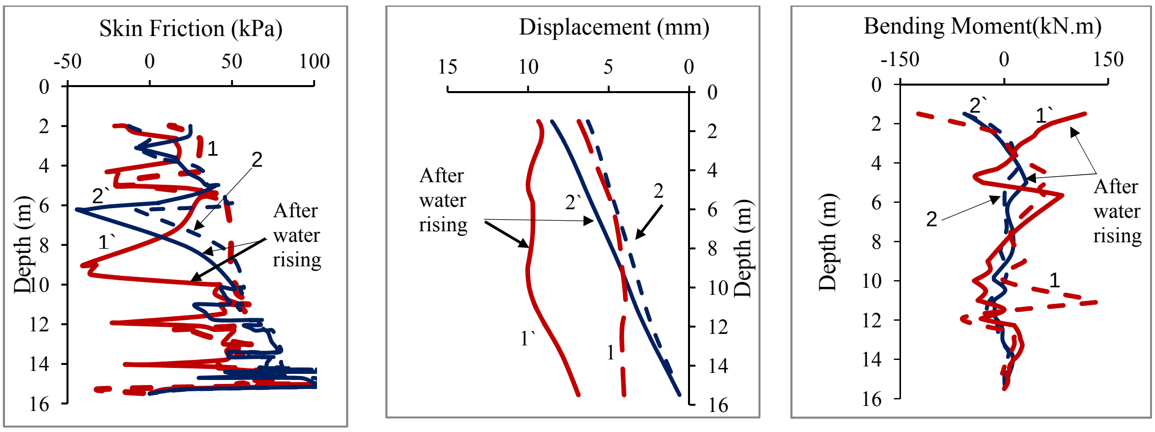


Figure 12. Soil settlement due to trenching and water rising.



Skin friction Horizontal displacement Bending moment

Figure 13. Piles skin friction, Horizontal displacement and bending Moment before and after water rising

6. Numerical parametric study

A simple parametric study based on numerical analysis was presented in this section. Finite difference analysis was used for such study. The main purpose of the parametric study is to find out the critical situation that could cause damage or high movement to the pile element near the trench. The possibility of slurry reduction or changes in groundwater levels was simulated for different pile positions from the trench. Additional simulation was made for slurry reduction at some locations which represent the case of presence of very course soil layer or cavities at these locations.

6.1. Main parameters and models

A total of 48 model analyses were made in this parametric study. The general variables are described in Figure 14. The soil was modelled using strain hardening softening soil model, while the pile element was used in modelling the pile. The modelling phases started by placing the pile in its position. Then the soil element at trench location was removed and replaced with slurry pressure.

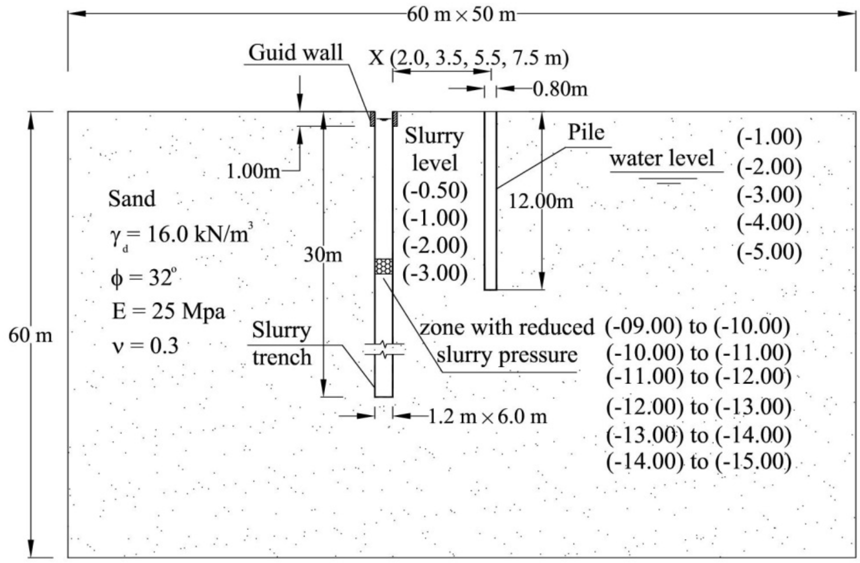


Figure 14. Parametric study main variables.

6.2. Parametric study results

The effect of different parameters on pile horizontal displacement and bending moment are presented and discussed in this section. The effects of slurry and groundwater level are presented in Figure 15 and 16. The groundwater level effect was studied for a pile at distance of 3.5m from the trench with a slurry level of 0.5m. The horizontal deformation increases by the increase of water level. The shape of the horizontal displacement varies according to the different water levels. Generally the pile tip is moving more than its top in all groundwater levels except for levels (-4.00) and (-5.00). The change in groundwater table causes the bending moment shape to change; without a noticeable change in its values. The groundwater table was fixed to be 2.0m below ground surface in order to find out the effect of slurry level. The bending moment and horizontal displacement are almost not effected by changing slurry level up to 2m below ground surface. The pile top shows a relatively significant movement toward the trench as the slurry level was 3.0m below the ground surface. The bending moment also increases in the positive direction when the slurry level was 3.0m below ground surface. The reason for the big changes in pile behaviour at slurry level of 3.0m is due to the failure of the trench at such level.

Effects of reduced slurry pressure at some levels are presented in Figure 17 and 18. The reduction in slurry pressure is presented for a pile distance of 3.5m, water level of 2.0m and slurry level of 1.0m. The maximum displacement and bending moment recorded for reduced pressure at levels between 12.0m and 13.0m (pile tip location).

The distance of pile from the trench is considered to be a major factor that affects the pile behaviour. The horizontal displacement and bending moment of the pile are reduced with distance from the trench. The horizontal displacement for piles at 3.5m distance from the trench is about 25%less than piles at distance 2.0m from the trench. While piles at distance 7.5m from the trench is about 62% less than the nearest piles to the trench. The shape of bending moment is greatly affected by pile location. Additionally, the values of bending moment were higher for piles near the trench than piles at distance from the trench.

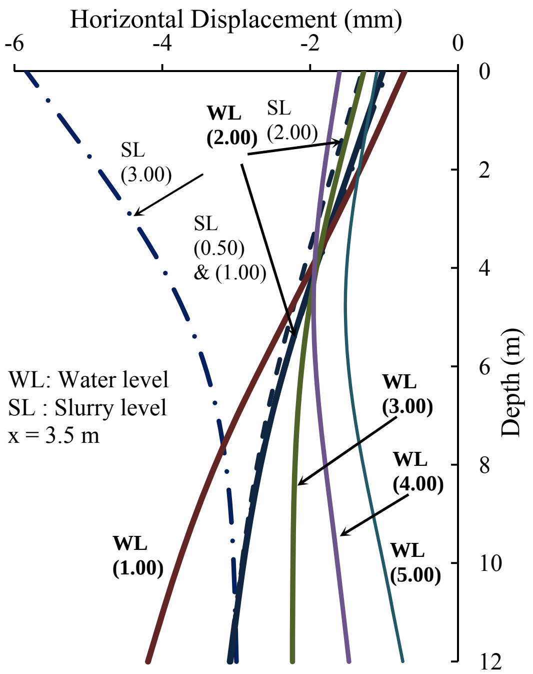


Figure 15. Effect of water and slurry level on pile Horizontal displacement

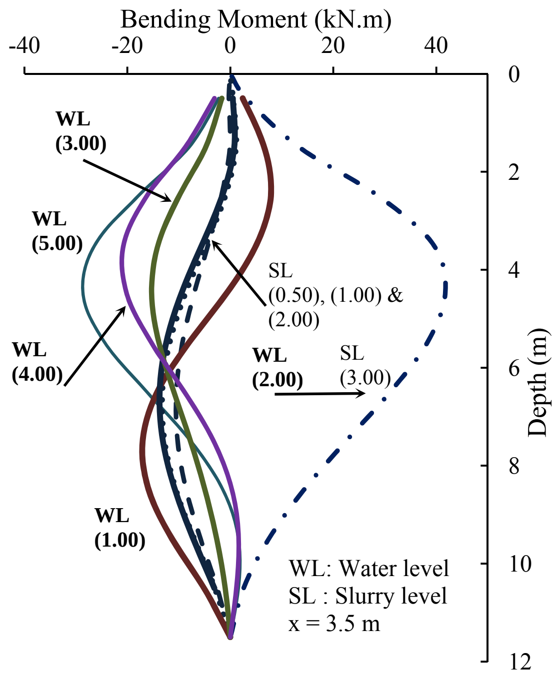


Figure 16. Effect of water and slurry level on pile Bending moment

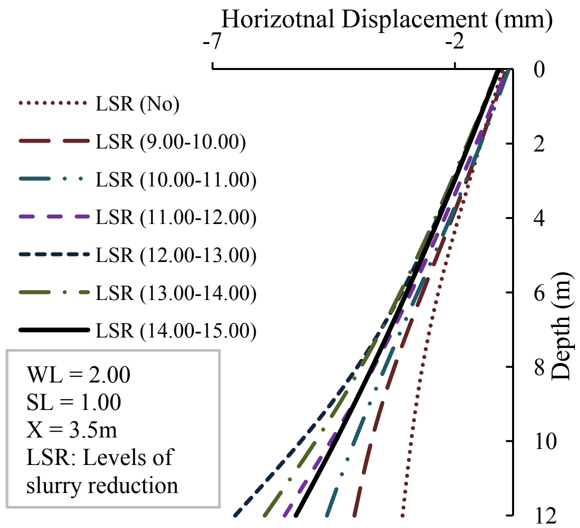


Figure 17. Effect of slurry level reduction at some levels on horizontal displacement.

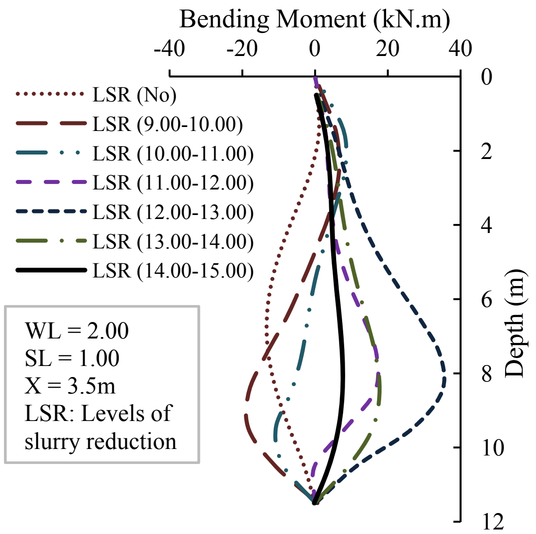


Figure 18. Effect of slurry level reduction at some levels on Bending moment.

7. Conclusions and recommendation

The results of the finite difference and centrifuge model tests regarding soil settlement was in better agreement than results regarding pile horizontal displacement and bending moment. The pile results

from centrifuge model tests were not reliable at some cases, as the pile could be subjected to eccentric load during the centrifuge model test. However, the results from the centrifuge and finite difference analysis provided the same general trend of pile behaviour. The horizontal displacement and bending moment of the pile increased with slurry reduction. The skin friction of the pile increased due to the decrease in end bearing. The pile end bearing decreased when the slurry reduced to about 40%. The trench length has a significant effect on the pile horizontal movement and bending moment.
Finite element results and field results were in a good agreement regarding soil settlement during trenching. The soil heaved due to water rising. However, piles near the excavated panel moved horizontally. The shape and values of bending moment for such piles were changed. The skin friction values show reduction contradicted with centrifuge model tests and finite difference results because the pile end bearing in this case was almost constant.
The changes of the groundwater level and slurry level were studied in the numerical parametric study. The slurry level at level 1.0m below the groundwater table caused the piles within distance of 0.2H from the trench to deflect significantly. Such deflection could cause instability to the pile and the whole structural system. Groundwater rising causes an increase in piles deflection. The shape of pile deflection was affected by the groundwater level. The reduction of slurry pressure at some levels causes additional deformation and bending moment for the pile. The reduction of slurry pressure at pile tip level has the highest effect on the pile horizontal movement and bending moment.
The increase of water table due to flood or other reason could cause damage to the piles near the slurry trench. The slurry level is the greatest parameter that could cause collapse in trench and damage to the nearby piles. The failure of the trench may not always cause a failure on the nearby pile; the failure shape is a main factor affecting the behaviour of the nearby piles. Precautions should be made regarding slurry level during trenching near deep foundations include keeping the slurry trench in its level. If the groundwater rises, an increase of the slurry level is highly recommended. A high quality soil investigation is required to observe any lenses or cavities of course soil that could cause a leakage of slurry into the soil and reduces its pressure in such locations.
It is recommended to widen the parametric study to include the effect on pile length and diameter. The pile group should be also taken into consideration. Different soil properties should be included in such study. The effect of trenching on pile skin friction and end bearing should be better clarified.

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