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TECHNICAL NOTE

The influence of trenching diaphragm wall panels on deflection and bending moment of existing piles within piled foundation

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Abstract Conducting deep excavations for underground construction inside the cities requires diaphragm wall due to space limitation. The ground surface is affected by the trenching process. The construction of the diaphragm walls near deep foundations may not be avoided specially in the crowded cities. This research focuses on the deflection and bending moment of piled foundations near slurry trench. Since the trench is considered as a three-dimensional problem, a three-dimensional numerical analysis was used in this research. It was conducted using a commercial analysis software known as FLAC 3D. The numerical analysis method was verified using two case histories, one in Hong Kong and another one in Giza, Egypt. The results from the numerical analysis were in quite a good contrast with the field data results. This indicates that the trenching process could be numerically modeled with the proposed method and provides good results. The verified numerical analysis method was used to conduct a numerical parametric sric study that discusses the effect of multiple panels on adjacent connected pile groups or piled raft foundation. The parametric study showed that the pile deflection and bending moment are affected by the panel construction stages, pile location within the foundation. The pile deflection and bending moment are affected by the stages of construction. The piles near the trench are affected by the trenching process, while the piles far from the trench are affected by the dragging force of the pile near the trench.

Keywords Diaphragm wall · Pile · Trenching · Deflection · Pile group · Pile raft foundation · Numerical analysis

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Introduction

The soil deformation caused by the diaphragm wall trenching process was monitored by many researchers. In general, they used the settlement points to measure the surface soil settlement and inclinometers to measure the horizontal soil displacement. The deep soil settlements were also measured in some cases. Monitoring during trenching process was made for either tested panel or multiple panels. DiBiagio and Myrvoll [7], Tsai et al. [21], and Ng et al. [18] had intensely monitored tested panel for research purposes, while Karlsrud [12], Cowland and Thorley [5], Hamza et al. [10], Poh et al. [19], and L'Amante et al. [14] monitored the diaphragm wall installation of case histories in real projects. The monitoring results were varied according to many parameters such as panel dimensions, groundwater level, and soil properties.

Trench panels were simulated using three-dimensional numerical analysis by Ng and Yan [17], Gourvenec and Powrie [8], Grandas-Tavera and Triantafyllidis [9], and Comodromos et al. [4]. These researchers compared the results from the numerical analysis with that from the field data. They used numerical analysis different tools to model the trenching process. They found out that thee three-dimensional numerical analysis is the best way to simulate the diaphragm wall trenching process.

In general, the trenching process causes settlement and horizontal displacement for the ground surface which could probably affect the nearby existing deep foundations. However, a very limited research has been made regarding such effect. Davies and Henkel [6], Abdel-Rahman and El-Sayed [1], and Korff [13] monitored the trenching process near existing piled foundation, but they were not able to monitor the existing piles. Choy et al. [3] studied the effect of the trenching process on a single pile using the centrifuge model test through conducting a limited parametric study. His study did not take into consideration the effect on pile group and the possible existence of groundwater.

In this research, the three-dimensional numerical analysis was used to simulate the trenching process of multiple diaphragm wall panels adjacent to deep foundation for two different case histories. The results from the numerical analysis were compared to the field data results. Such simulation method was used to conduct a parametric study which discusses the effect of diaphragm wall panels' installation on the existing connected pile group or piled raft foundation.

Numerical analysis of case histories and verification

The numerical modeling for different geotechnical engineering problems is considered to be an acceptable tool. However, the modeling method of the different types of such problems should be verified. The trenching process of slurry trench walls required a three-dimensional simulation with a special attention to the stages and simulation assumptions. Two case histories were modeled numerically in this section using FLAC 3D. The results from modeling were compared to those from the field.

Case history 1 (underground station near the court of justice in Hong Kong)

A diaphragm wall system was used as a part of the Charter underground metro station. This station was very close to the court of justice which was constructed in a timber piled foundation. The piles' cross-sectional area was equal to 0.0254 m^2 and it extended to a level of 14 m beneath the ground surface. The building load was distributed over the beams that connect the piles. The details of the project are described by Davies and Henkel [6]. The numerical modeling and verification related to the diaphragm wall panels' construction adjacent to the building are described in the following subsections.

Modeling and construction stages

The construction stages of the diaphragm wall panels were modeled, as described in Fig. 1. According to Stround and Sweeney [20], the soil was found to be consisted of five layers. The soil layers' depths and their properties are presented in Table 1. The soil was modeled using strain hardening softening soil model which is defined in FLAC 3D by conducting a relation between mobilized friction angle and plastic shear strain which can be calculated according to Byrne et al. [2] as

$$\xi_p = \frac{P_{\text{ref}}}{\beta G^{e}_{\text{ref}}} \times \frac{\sin\varphi}{R_f}\left(\left(1 - \frac{\sin\phi_m}{\sin\phi}R_f\right)^{-1} - 1\right), \quad (1)$$

where P_{ref} is the reference pressure, β is the calibration factor, ϕ is the ultimate friction angle, ϕ_m is the mobilized friction angle, and R_f is the failure ratio. The elastic tangent shear modulus is calculated from the following equation:

$$G^{e}_{\text{ref}} = \frac{E^{\text{ref}}_{\text{ur}}}{2(1+\upsilon_{\text{ur}})}, \quad (2)$$

where $E^{\text{ref}}_{\text{ur}}$ is the required strain to mobilize the limit friction angle, and ν_{ur} is the undrained Poisson's ratio.

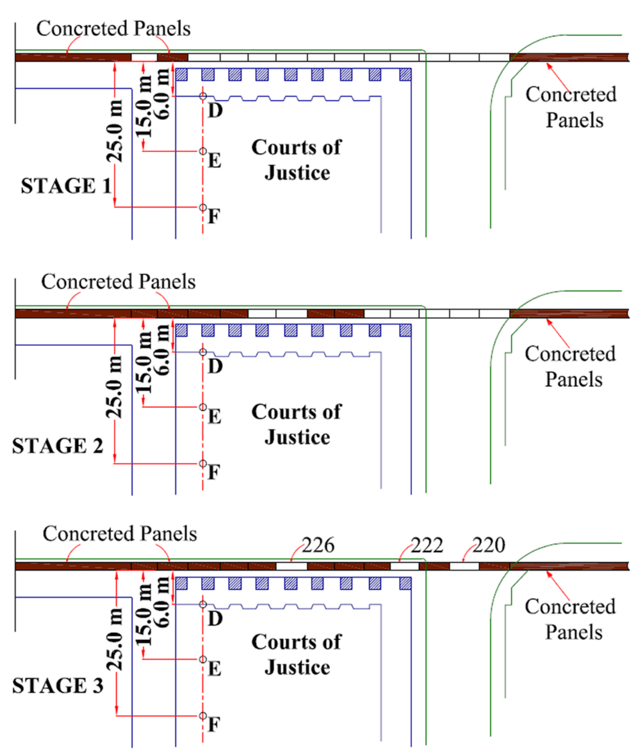

Fig. 1 Courts of justice construction stages and points of monitoring

Table 1 Soil properties (Courts of Justice, Hong Kong)

Soil layer	Bottom level (m)	SPT	γ (kN/m^3)	c'/cu (kN/m^2)	ϕ' (°)	E (MPa)
Fill	− 1.0	5–30	17.0	0	27	10
Marine deposits	− 2.6	5–30	17.0	5/35	15	10
Highly weathered decomposed granite	− 11.0	10–20	17.62	0	30	40
Decomposed granite	− 31.75	> 40	20.0	0	36	85
Granite	–	–	22.2	0	40	100

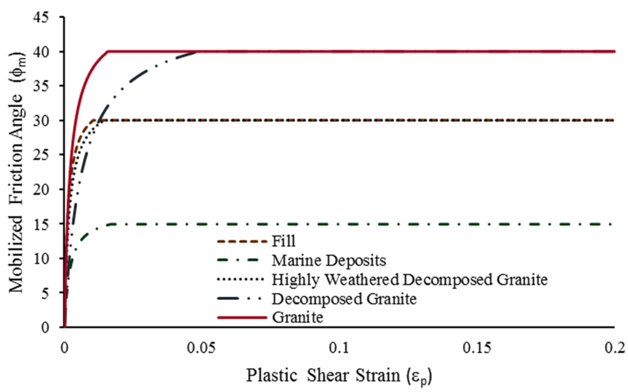

Fig. 2 Relation between mobilized friction angle and plastic shear strain for different soil layers

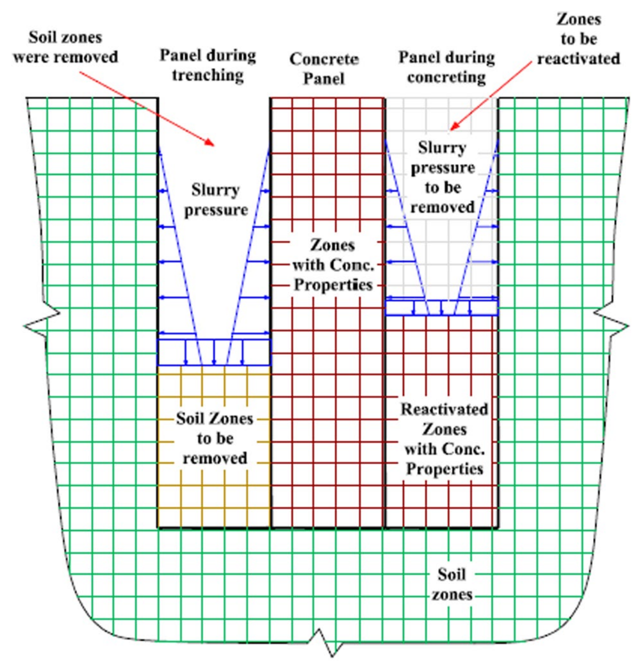

Fig. 3 Trench modeling process

The relation between the plastic shear strain and mobilized friction angle based on the previous equations for the soil layers is presented in Fig. 2.

The trenching process of each panel was made by replacing the soil elements at the panel location with a hydrostatic pressure equivalent to the slurry pressure. The concreting process of the panel is made then by reactivation of the zones and changing its properties to concrete properties. Figure 3 shows the trenching process of a panel in different situations. The pile and beams connecting the piles were modeled using the beam and pile elements, respectively. These elements are described and discussed by Itasca [11]. The mesh model contains 157,800 zones and its shape and dimension are presented in Fig. 4. The relative normal and shear displacement between the pile and the soil are defined by the normal stiffness K_n and shear stiffness K_s, respectively. They are considered to be equal and can be calculated from the following empirical equation:

$$K_n = K_s = 10\max\left[K + \frac{4G}{\Delta z_{\min}}\right], \quad (3)$$

where k is the soil bulk modulus, G is the soil shear modulus, $\Delta z_{\min}$ is and the minimum distance in the vertical direction of the mesh.

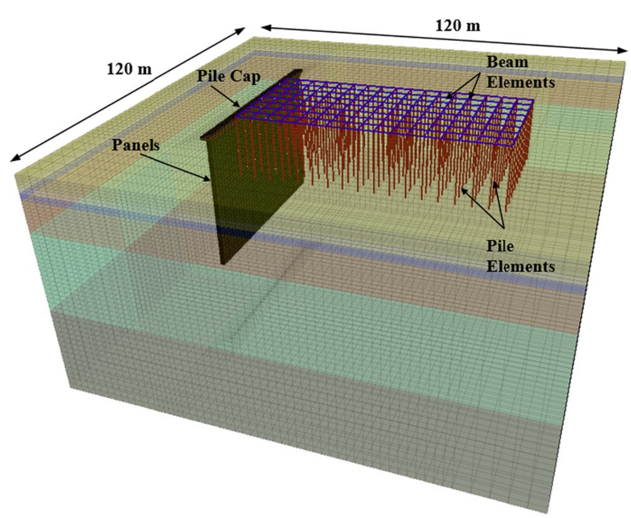

Fig. 4 Mesh geometry of trench near curt of justice

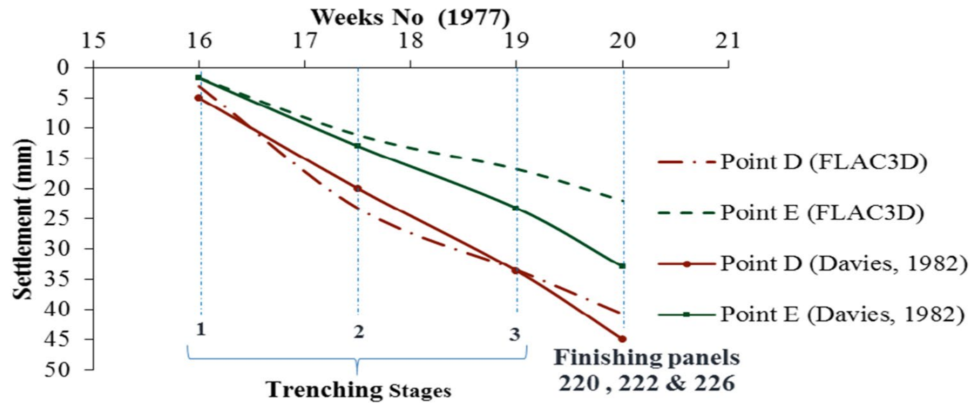

Fig. 5 Settlement at different stages

Table 2 Soil properties (Basement near piled foundation, Giza)

Soil layer	Bottom level (m)	SPT	γ_b (kN/m^2)	ϕ' (°)	E_{oed} (MPa)	E_{ur} (MPa)
Fill	– 2.0	–	17.0	28	16.0	48.0
Silty sand	– 5.0	12	18.0	30	17.0	49.0
Medium sand	– 11.0	20	19.0	33.5	36.0	108.0
Dense sand	– 25.0	42	20.0	36	42.0	124.0

Results and comparison

The settlement results of the numerical analysis compared to field data for points D and E at different stages are presented in Fig. 5. The results showed that the settlement values increase with stages and decrease with the distance from the trench.

The values of settlement from the numerical analysis nearest to the trench (point D) were in a very good agreement with those from the field data. This good agreement was not found in case of comparing the results at point E. In general, the comparison showed that the numerical analysis provides reliable results that can present the reality.

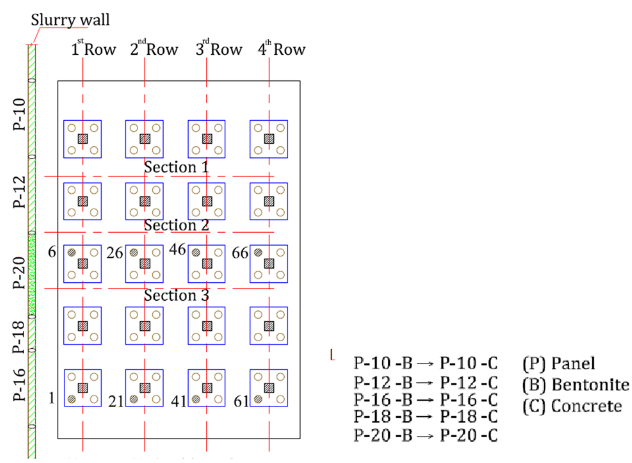

Fig. 6 Construction stages of the panels adjacent to the studied building

Case history 2 (basement near high-rise buildings in Giza, Egypt)

The underground construction of a basement in a crowded area in Giza, Egypt was done using diaphragm wall technique. The construction area was surrounded by several buildings as described by Abdel-Rahman and El-Sayed [1]. The soil was mainly sand and it was simulated using the same soil model that was used in the first case history. The soil properties are shown in Table 2. The panels' construction stages are presented in Fig. 6 and they were modeled as in the field. Each panel was modeled as previously described and as shown in Fig. 3.

The piles and the grade beams connecting the pile caps were modeled as described in the first case history. The pile caps were modeled using the shell elements and they carry the building load. The mesh used to simulate this case history is presented in Fig. 7.

The results from the numerical analysis compared to those from the field are presented in Fig. 8. The comparison was made for the three sections. The values of settlement were measured during trenching of the last panel (i.e., stage P-20-B) and it shows a decrease with distance from the trench. There was a slight difference regarding the settlement shape between the field and the numerical analysis. The settlement values from the numerical analysis adjacent to the trench and at a distance of 19 m from the trench are identical with those from the field, but the settlement values from the numerical analysis

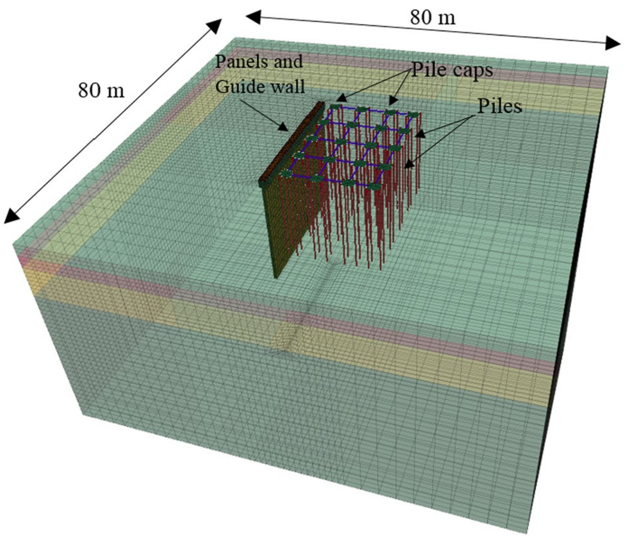

Fig. 7 Mesh geometry of the trench near the multi-story building

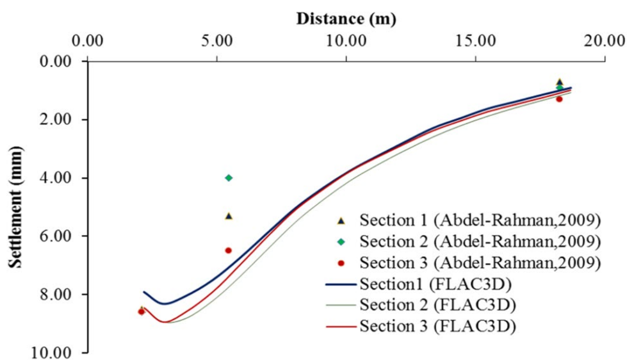

Fig. 8 Settlement at the last stage for different sections

were slightly higher than those from the field at a distance of 5 m from the trench. In general, the output from the numerical analysis is in a good contrast with the field results.

Numerical parametric study

The numerical simulation and comparison for the presented case histories showed that the method of simulating the trench numerically is acceptable and provides reliable results. This research provides a more realistic cases than that was presented by Mohamed et al. [16]. It provides the effect of trenching process of multiple panels on adjacent connected pile groups, as shown in Fig. 9, or piled raft foundation, as shown in Fig. 10.

Studied parameters

The soil used in this study was sand with a friction angle $\phi = 32°$, a bulk density $\phi_b = 18$ kN/m^3, and shear modulus $G = 9.6$ MPa. The pile depth was 12 m and its diameter (D) was 0.8 m in all cases. The panel depth was chosen to be 30 m, because below this depth, the pile with a 12 m depth will almost not be affected [15]. The trench length (L) was either 6 m, while its thickness (T) was 1.2 m. The slurry and groundwater levels were chosen to be 0.5 and 2 m below the ground surface, respectively. The diaphragm wall was constructed using nine panels and it was conducted in stages from 1 to 9, as shown in the figures.

Results from the parametric study

The effect of panels' construction stages on connected pile groups is shown in Fig. 11, while the effect of panels' construction stages on piled raft foundation is shown in Fig. 12. The tip of the pile nearest to the trench deflects higher than its tip also showed a decrease in deflection at its tip with advancing in panels' construction because. The pile top showed an increase during construction of the panels, because the whole movement of the raft is increased with advancing in construction. The bending moment showed a change from negative to positive values with panels' construction. In general, the change in deflection and bending moment values was great during constructing the initial panels.

The effect of constructing the entire wall on individual pile groups defined by rows parallel and perpendicular to the trench is presented in Fig. 13. The maximum deflection was for the pile groups located near the centerline of the entire trench wall. The pile group located at the edge of the raft showed the lowest value of deflection. The difference between the piles of the first row was between 1 and 50%. The bending moment results of the piles did not show a fixed noticeable difference, because the whole system is acting together. However, the piles in the middle showed relatively larger values which were about 10% higher than the average other piles' values. The deflection and bending moment of the middle (fifth) row perpendicular to the trench are presented in Fig. 14. The deflection of the first pile group within the pile row was much greater than that of the other piles regarding the pile tip. However, regarding the top of the pile, there was no big difference between the piles and they almost move in the same way. This is because the soil movement affected the tip of the pile near to the trench, while the other piles were affected by the drag forces.

The comparison between the different piles within raft and in the first row parallel to the trench is shown in Fig. 15. The piles' tip deflection, which is located within the row, was more than 100% higher than piles at the edges. However, the

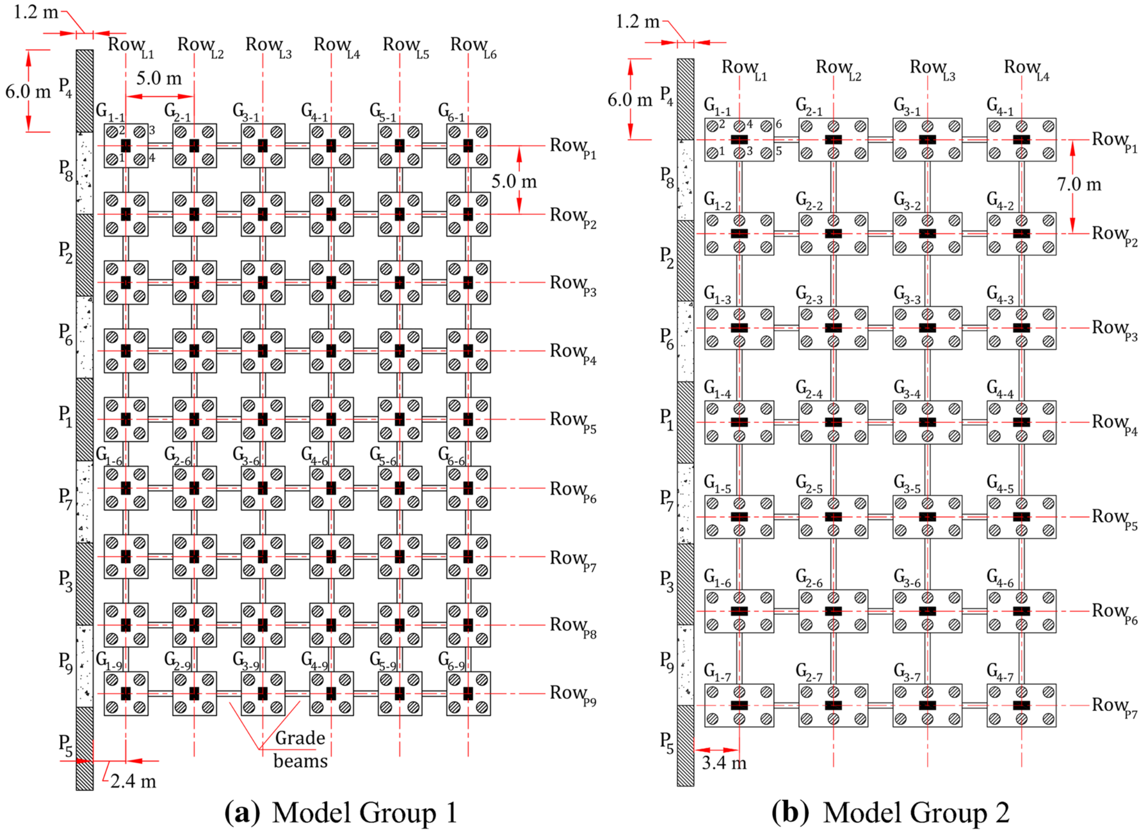

Fig. 9 Diaphragm wall near connected pile group

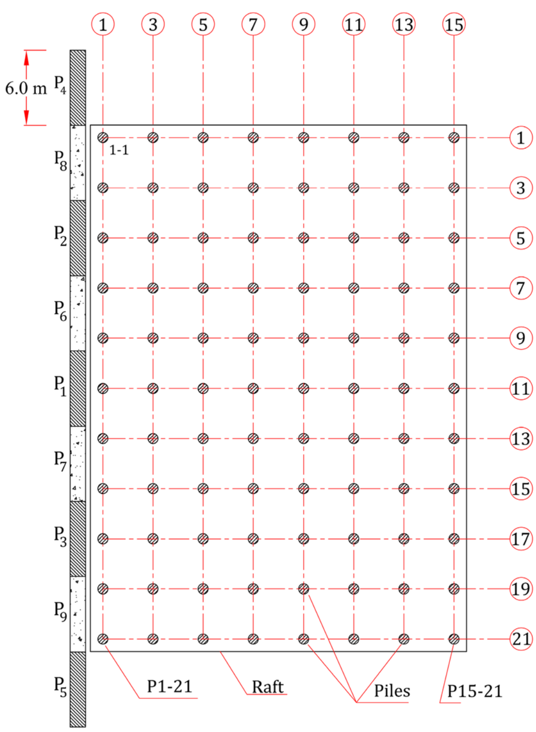

Fig. 10 Diaphragm wall near piled raft foundation

bending moment values did not show such a big difference which was less than 50% as an average value.

Conclusions

Two different case histories were used to verify the ability of numerical simulating trenching process adjacent to deep foundation. The settlement results from the numerical analysis and field data were in good agreement. However, some differences between both results were found due to the random nature of the field data results. The numerical analysis depends on mathematical relations and provides systematic results.

The deflection and bending moment of the piles within connected pile group or piled raft foundation due to trenching process of multiple panels were presented through a parametric study.

The pile tip is deflected by advancing on construction stages as it can be increased or reduced according to the pile location within the raft or connected pile groups. However, the top of the pile shows a general increase in deflection values with the advancing on construction stages, because it is affected mainly by the general

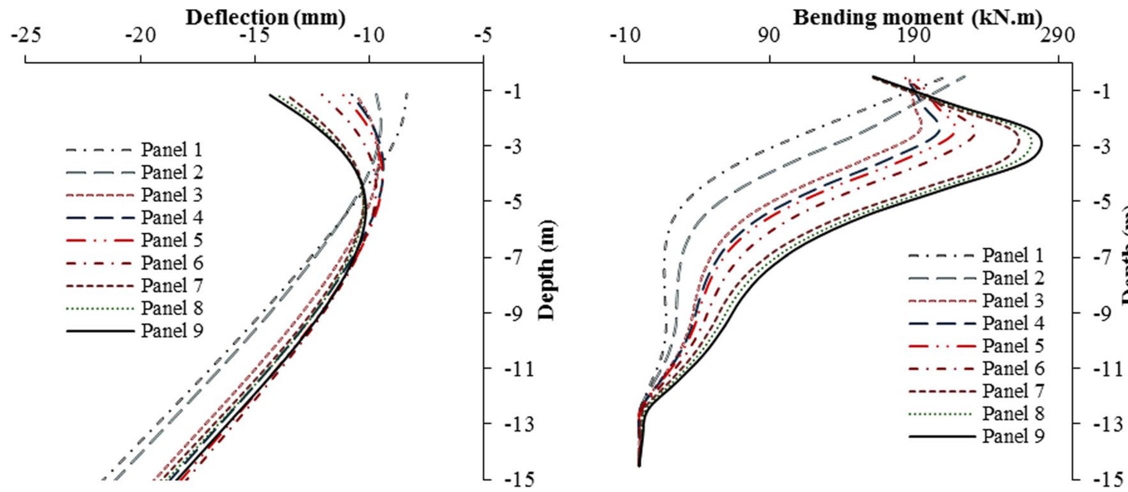

Fig. 11 Effect of panels' construction stages on connected pile group deflection and bending moment

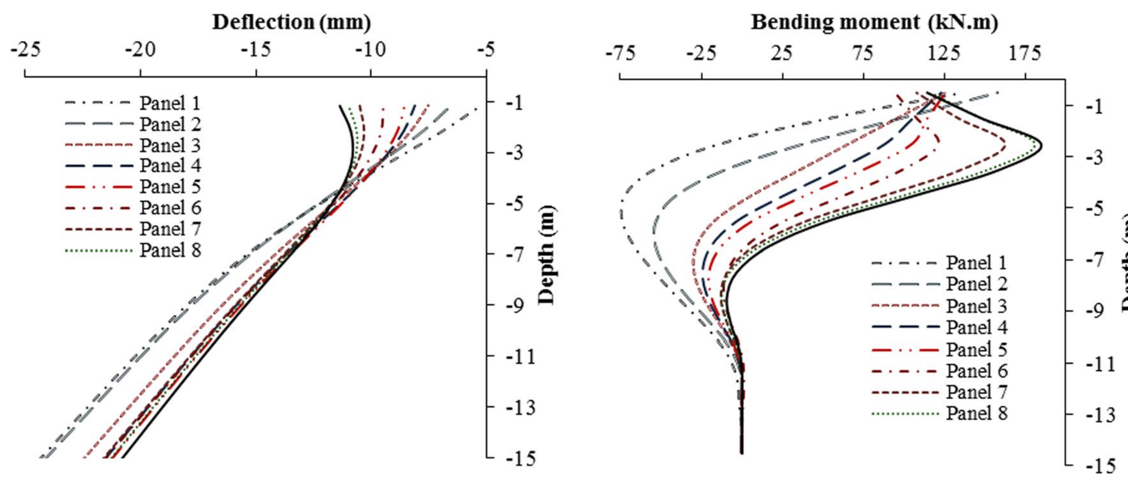

Fig. 12 Pile deflection and bending moment at different panels' construction stages for piles P1–11 of the pile raft foundation

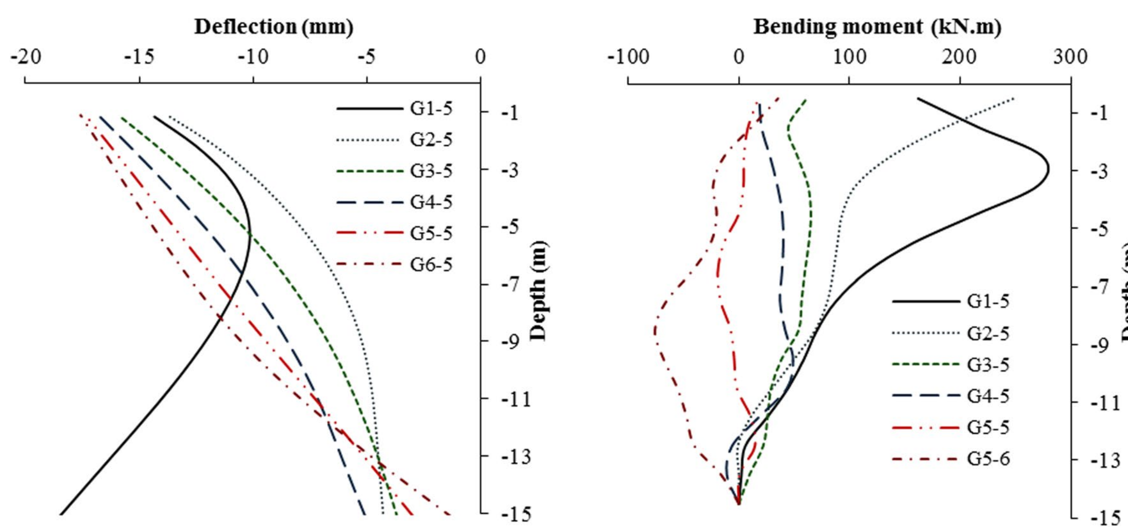

Fig. 13 Piles' deflection and bending moment for the first pile within the indicated connected pile groups (perpendicular to the trench)

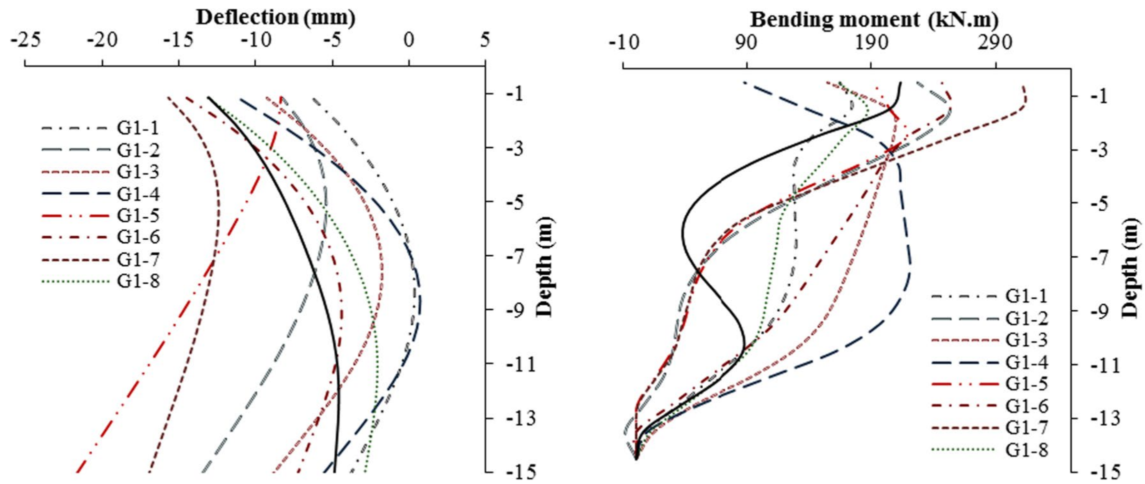

Fig. 14 Pile deflection and bending moment for the first row of the connected pile groups parallel to the trench

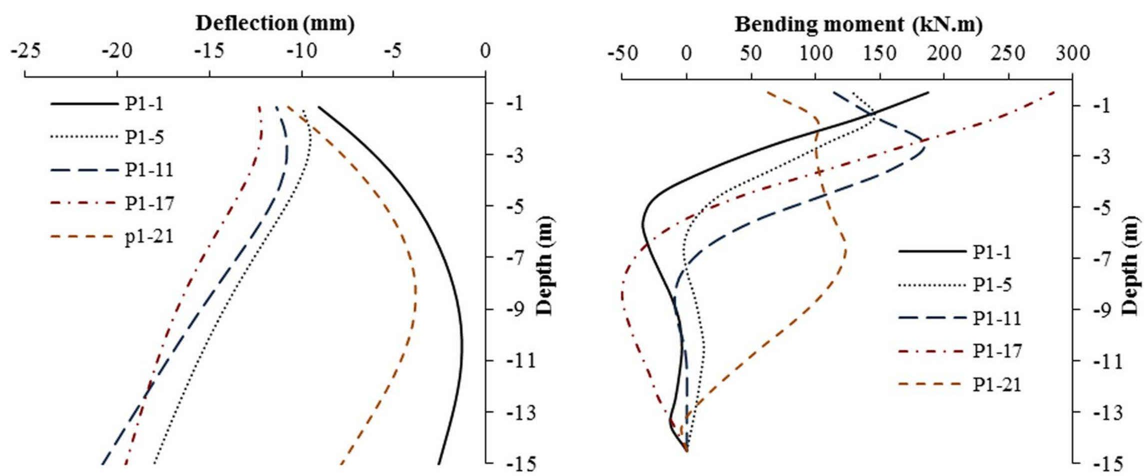

Fig. 15 Pile deflection and bending moment for piles within the first row parallel to the trench within the piled raft foundation

movement of the group. In general, the bending moment values increased in positive values.

The pile in the middle of the row parallel to the trench shows higher deflection values than those in the edges. There was a difference in bending moment values as well.

The pile nearest to the trench deflects from its tip greater than it top, because it is affected directly by the trenching process, while the piles far from the trench deflects from their top relatively greater than their tip, because they affected by the dragging force from the front piles. The bending moments for the piles nearest to the trench were positive, while the piles far from the trench were tending to be negative.

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