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INVESTIGATION OF THE BEHAVIOR OF SUPPORTING STRUCTURE SYSTEMS AND FINDING THE OPTIMAL METHOD FOR URBAN EXCAVATION

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ABSTRACT: Today, the increasing growth of urban construction as a result of urban development necessitates deep excavation in highly dense urban areas, therefore, supporting and securing excavation by appropriate methods have become of crucial importance. In such conditions, common and widely used methods of excavation support will be used by designing engineers. However, each of these methods has its own disadvantages and limitations. Therefore, these methods cannot be used in various conditions with different geotechnical and site properties. In such cases, an accurate analysis of the condition can help the engineers to select and design the supporting and stabilizing system. In this regard, different methods have been used by engineers, among which numerical methods have led to appropriate results. In this study, a series of numerical analyses by the finite element code PLAXIS2D was used for investigating the behavior of an excavated zone in the central region of Ahvaz which has complicated geotechnical and site features. For this purpose, four different and common methods of excavation support including tangent piles with anchorage, a deep soil mixing system with anchorage, tangent piles with struts, and a deep mixing system with struts were examined. The results clearly showed that tangent piles with struts gave the best results due to the rigid-like behavior of its components.

Keywords: Excavation Methods, Strut, Deep Soil Mixing, Finite Elements.

1. INTRODUCTION

Increasing demand for construction in high density urban regions as a consequence of fast city expansion has resulted in the need for deep excavation in most construction cases. Soil drilling and its released stress will change the behavior of the soil in the excavated zone and its surroundings. Such alteration will often lead to displacements in the excavated zone and its surrounding structures [1-3]. Therefore, the lack of proper and accurate soil analysis during excavation might result in irreparable damage to the excavation zone and its surrounding structure as a consequence of the stress-deformation field of drilling. In such cases, correct and precise prediction of the soil behavior and the induced deformation can prevent possible damage. In this content, various methods including analytical and numerical analyses and experimental modeling have been investigated for a better understanding of soil behavior during excavation [4,5]. Due to the time and validity limitations of experimental modeling, such methods (i.e. centrifuge experiment) cannot be regarded as a realistic method for the investigation of excavation behavior and its impacts. In such cases, analytical and numerical studies have been conducted as an alternative method for examining the soil response to excavation [3, 6-8]. Recently, the enhanced computational capabilities of computers and also the better accuracy of numerical methods (compared with analytical ones) have made them among the most popular methods in excavation studies. In this study, for the investigation of the excavated zones' behavior in urban regions and selecting an optimal system for excavation support, the behavior and design of an excavated zone were studied. In this context, the support of an excavated zone in Ahvaz using different systems was analyzed and compared. For this purpose, conventional and common methods of urban excavation support such as tangent piles with anchorage, a deep soil mixing (DSM) system with anchorage, tangent piles with struts, and a deep soil mixing system with struts, were considered. First, each of these methods is briefly described and then they are numerically analyzed. Finally, based on the results of each analysis, an optimal support system will be presented for drilling and excavation in urban regions.

2. PROJECT FEATURES

This study investigated a site in the central region of Ahvaz which was considered for construction of a large hospital (Cancer Therapy Center of Ahvaz). Ahvaz soil has different stratifications in terms of material, grading and generally in terms of soil classification, in such a way that the substrate layer lies at different depths of the city; in other words, first the soil profiles from the northern half of the route consist mainly of fine grained clay and silty layers over the bedrock formation consisting of red marl, siltstone and sandstone at a shallow depth; secondly, the soil profiles from the southern half of the route on which the bedrock formation lies fall below a depth of 40 m under young alluvial deposits due to the presence of the Ahvaz fault. The young alluvial deposits consist of layers of fine to medium sand, clay and silt with low to medium density. Thus, in different parts of the city we will observe different resistance and settleability [9]. The depth of excavation was about 10 m and the geometry of the excavation plan had a rectangular shape with dimensions of 36.6x22.05 m. A high priority hospital (Taleghani Burn and Accident Injuries Hospital) is also located to the west of the excavation zone, which highlights the importance of the project. Fig. 1 depicts the position of the project.

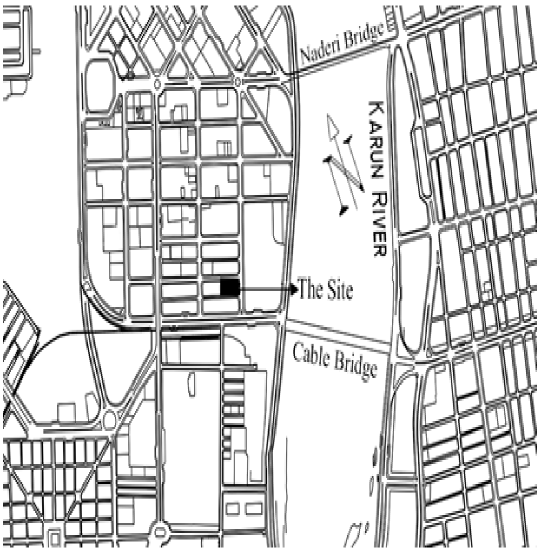

Fig. 1 Project site position- Ahvaz city near Karoon River

For implementation of the supporting structure in the Comprehensive Cancer Therapy Center, first, five wells (depth 20 m) were drilled to obtain disturbed and undisturbed samples for the required tests. Their positions are shown in Fig. 2 and Table 1 summarizes the test results of the samples.

Regarding the proximity of the project site to Karoon River, the static surface of the project site was located 5.4 m beneath the ground surface and the slope of water movement had a west to east direction. As the Taleghani Hospital building, at the west of the project site, is old and weak, a method is needed to prevent movement of sand and silt from beneath the building and their leakage to the excavation zone. According to Table 1, the in situ humidity was between the liquidity and plasticity limits and the values of penetration tests indicated good stiffness of the studied soil.

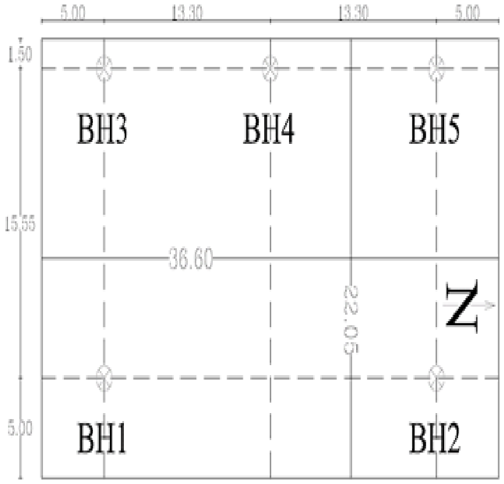

Fig. 2 Positions of boreholes for site investigation at the site location

3. METHODS OF EXCAVATION SUPPORT

As mentioned before, given the importance of this project, numerous methods of deep excavation in urban areas [10-12] have been examined for this project. These methods include four conventional methods which will be briefly described in the following**.**

3.1 Tangent Pile with Anchorage

In this method, piles are implemented around the excavation area at intervals determined by the project supervisor engineer. These piles can be made of different construction materials such as steel, concrete and wood. After pile implementation, excavation can be comfortably initiated. To provide lateral solidity and rigidity of the supporting structure, piles will be braced along the excavation zone wall simultaneous with the excavation procedure. This bracing will be done by nailing and anchorage systems; in this way, the lateral deformations of cantilever piles due to the lateral force of the soil at the back of the wall will be drastically reduced [11].

3.2 Deep Soil Mixing with Anchorage

Similar to tangent piles, in this method lime and cement columns mixed with the soil will be implemented around the excavated zone walls before excavation. In this method, the stabilizing agents cement or lime will be mechanically mixed with the soil using a drill with a hollow axis. The soil mixing process results in the formation of a uniform (constant width) column made from the soil and additives. By overlapping the columns before complete establishment, it is possible to construct continuous walls underneath the earth, which can resist lateral deformations like a cantilever system. By this method, modified geotechnical parameters such as compressive strength, shear strength and permeability will be achieved [10-12]; in the next step and after implementation of the lime and cement columns, nailing and anchorage will be implemented along with the excavation process. By implementing these systems, lateral deformations of the sealed wall, made of the lime and cement columns, will be controlled and therefore the internal forces of the supporting structure will be decreased substantially.

Table 1 Summary of soil properties at the site location

BH1	Depth(m)	Description	Wn	PL	LL	SPT	Silt %	Clay %	Sand %
	0-0.70	Fill Material							
	0.70-5.0	ML	12	NP	NP	28	40-46	29-35	25
	5.0-20.0	CL	19-23	19-20	34-46	24	40-50	48-58	7
BH2	Depth(m)	Description	Wn	PL	LL	SPT	Silt %	Clay %	Sand %
	0-0.70	Fill Material							
	0.70-5.0	ML	6	NP	NP	26	51	27	22
	5.0-20.0	CL	23	18-20	36-49	21	44-52	40-52	5
BH3	Depth(m)	Description	Wn	PL	LL	SPT	Silt %	Clay %	Sand %
	0-0.70	Fill Material							
	0.70-5.0	CL-ML	8-11	NP-14	NP-30	23	31-60	25-39	15-30
	5.0-7.0	CL	18	14	30	26	41	32	27
	7.0-9.50	ML	20-22	NP	NP	20	45	25	30
	9.50-12.0	CL	21	14	27	22	50	31	19
	12.0-14.50	CL	20-21	14	32	17	64	35	1
	14.50-20.0	CL	23-25	13-14	24-27	23	42-54	23-28	23-30
BH4	Depth(m)	Description	Wn	PL	LL	SPT	Silt %	Clay %	Sand %
	0-0.70	Fill Material							
	0.70-5.0	CL-ML	6-10	NP-14	NP-29	28	56-64	21-35	9-15
	5.0-7.0	CL	18	14	29	24	60	21	19
	7.0-9.50	ML	23	NP	NP	17	57	20	23
	9.50-12.0	CL	18-20	14	33	19	54	25	21
	12.0-14.50	CL	23-25	14	31	21	65	32	3
	14.50-20.0	CL	24	14	27	23	57	18-22	23-27
BH5	Depth(m)	Description	Wn	PL	LL	SPT	Silt %	Clay %	Sand %
	0-0.70	Fill Material							
	0.70-5.0	CL	7-9	12-14	30-32	27	60	35	3-7
	5.0-7.0	CL	25	22	30	24	46	35	19
	7.0-9.50	ML	25	NP	NP	18	51	22	27
	9.50-20.0	CL	24	14	27-32	25	44-64	21-29	15-27

3.3 Tangent Piles with Struts

Similar to tangent piles with anchorage, in this method, first axial load-bearing elements which are tangent piles will be implemented around the excavation zone walls using relevant machinery. After that, excavation will be carried out stepwise and, as excavation progresses, the excavation zone will be braced and retrofitted with struts [13,14]. Reciprocal bracing (struts) not only increases the loading capacity of the vertical components and supporting structure, but considerably reduces the deformations in the vertical components, which will result in a reduction of possible collapses and deformations in the soil at the back of the wall. The importance of this method is highlighted when high priority buildings exist adjacent to the excavated zone.

3.4 Deep Soil Mixing with Struts

Similar to deep soil mixing with anchorage, first axial load-bearing elements, the lime- and cement-mixed soil columns, are implemented around the excavated zone walls. Then the excavation process will be implemented stepwise along with reciprocal bracing (struts). As a result of this type of supporting system, resistant and load-bearing components will be braced against the lateral loads imposed from the back of the walls, and the induced deformations and displacements will be drastically reduced. The utilization of deep cement mixing (DCM) in excavation serves not only the support system, but also as a ground improvement for soft soil in the passive zone of an excavation [15].

Table 3 Mechanical and physical properties of different elements used for simulation

System	d(cm)	EA (kN/m)	EI (kNm^2/m)	L_S (m)
DSM	35	3.284e6	3.267e4	---
Piles	70	1.583e8	6.333e6	---
Struts	-----	3.9e6	-------	5
Anchor	-----	1.5e5	-------	2

4. NUMERICAL SIMULATION

Numerical simulation of this study was carried out by PLAXIS2D finite element code. As mentioned before, an excavation zone in the central region of Ahvaz was selected for investigation of the behavior of the excavated zone and for designing a suitable supporting system. To simulate the construction steps in the software, first the model geometry of each mentioned excavation method was modeled. Then the standard boundary conditions were defined. Next, soil resistance features and hydrostatic conditions were defined for the software. After compilation of the model geometry and features of the layers, system meshing was performed. Based on the geotechnical studies, the soil layers are mainly composed of fine-grained materials such as sediments, clay and sand. To simulate the soil behavior, this analysis employed the Soil Hardening behavioral method, which is an elastic-plastic model with a hardening capability. Table 2 lists the soil shear strength parameters used in this study.

Table 2 Soil parameters used in FEM analyses

Soil	CL	CL	ML	ML	ML
E_{50}^{ref} (MPa)	10	10	15	10	10
E_{oed}^{ref} (MPa)	10	10	15	10	10
E_{ur}^{ref} (MPa)	30	30	45	30	30
M	0.5	0.5	0.5	0.5	0.5
C_{ref} (kPa)	1	0.1	40	0.1	0.1
φ^o	28	26	6	25	26
$\gamma\,(kN/m^3)$	17	18	18	18	17

As mentioned before, different systems were investigated and compared for excavation support. For the modeling of these systems, relevant elements were used in the software. Table 3 tabulates these components and their strength parameters.

After complete definition of the models' geometry, the excavation process was simulated by the different methods of supporting systems. For this purpose, six different computational phases were considered in the software, in which excavation and supporting implementation were applied relative to the supporting method.

5. RESULTS AND DISCUSSION

This section is dedicated to the analysis and investigation of the numerical simulation of excavation to identify a suitable method for the studied excavation zone. A series of 2D analyses were performed and their results were compared. The results of wall horizontal deformation, vertical deformation of the excavated zone floor and bending moment in the supporting structure walls were investigated to compare the different systems in terms of their technical performance.

5.1 Horizontal Deformation of Excavated Zone Wall

Horizontal deformation of the free ends of the walls was investigated and compared to study the performance of each excavation supporting system. Table 4 lists the results of analyses for horizontal deformation of the free ends of the excavation zones. Figure 3 also shows the wall deformation in any of these states.

Table 4 Horizontal deformation amounts of free ends of excavation zones

System	Horizontal displacement (mm)
DSM+Anchor	81
Pile+Anchor	20.14
DSM+Strut	32
Pile+Strut	5.2

As can be seen, the tangent pile system with struts had the smallest horizontal deformation in the free ends of the excavation zone walls. This could be due to high stiffness of the piles and reduction of the free walls' length as a result of the very hard struts. In fact, this system's good performance can be partly attributed to appropriate performance of the piles due to their high stiffness, and also relates partly to the effective performance of the struts in reducing the critical length of the supporting structure wall. Both these factors led to a drastic reduction of horizontal deformations. Comparison of the results also indicated that the use of piles in the walls of the supporting structure will lead to better results than the employment of cement and lime columns. This reveals that the supporting system's ability to enhance the stiffness and reduce the soil manipulation (which can reduce the effects of soil inhomogeneity) will considerably reduce the deformations.

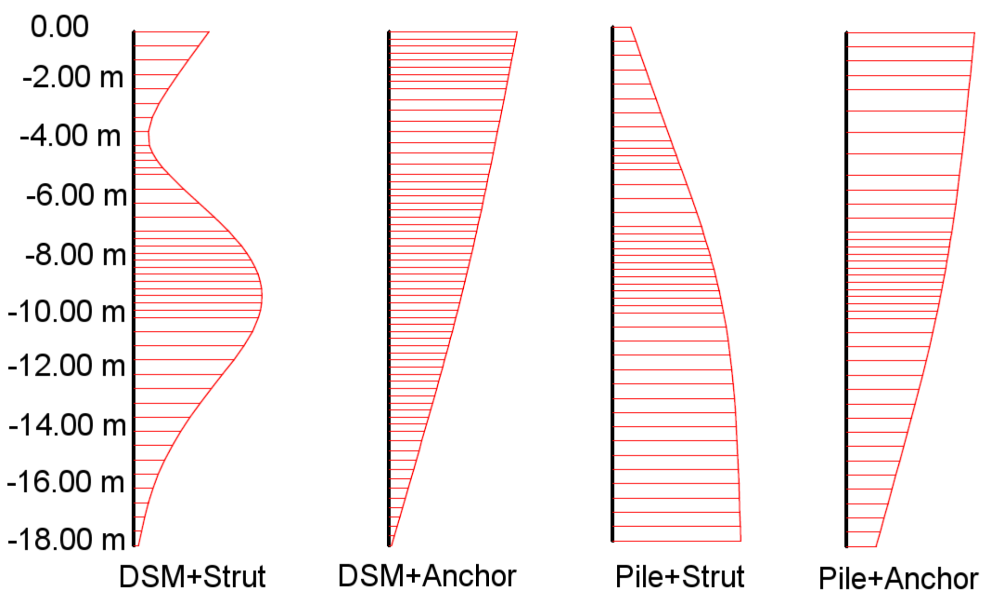

Fig. 3 Horizontal walls deformation and displacement in analyses

5.2 Floor Vertical Deformation (Upheaval of the Floor)

Through the excavation and drilling progress, vertical deformations will be induced in the floor of the excavated zone. Table 5 presents the vertical deformations for all the studied systems.

Table 5 Vertical deformation amounts in the floor of the excavated zone

Vertical displacement(mm)	System
54	DSM+Anchor
26.75	Pile+Anchor
88	DSM+Strut
61	Pile+Strut

As can be seen, front bracing systems (strut-assisted systems), in comparison with back bracing systems (anchorage systems), showed higher values of vertical displacements. In fact, with progress of the excavation and increase of the unloading rate, compressive forces will be created in the struts, whose magnitudes are far greater than the tensile forces in the anchorage elements (Table 6). As a result, these forces will induce more rotation in the supporting walls at the pivot location; therefore a larger deformation field will be created in the vicinity of the walls' pivots.

Also, comparing the floor upheaval in the pile-assisted supporting method with that of DSM, clearly showed that by increasing the stiffness of the elements of the excavated zone walls, the walls' resistance against excavation-induced deformation will increase and therefore the stress-displacement field and wall rotation will be reduced.

5.3 Internal Forces of Walls

For a more comprehensive and accurate investigation of the systems to find an efficient and appropriate system for the excavation supporting structure and bracing, the results of the internal force of load-bearing elements of the excavated zone walls were studied for each of the systems, as tabulated in Table 7. Fig. 4 also depicts the bending moment shearing force of the wall for each system.

Table 6 Magnitudes of support elements in different systems

System	Tensile force in anchorage element (kN/m)			Compressive force in strut element (kN/m)
DSM	161.8	63	18	476
Pile	127.8	102.8	100	307

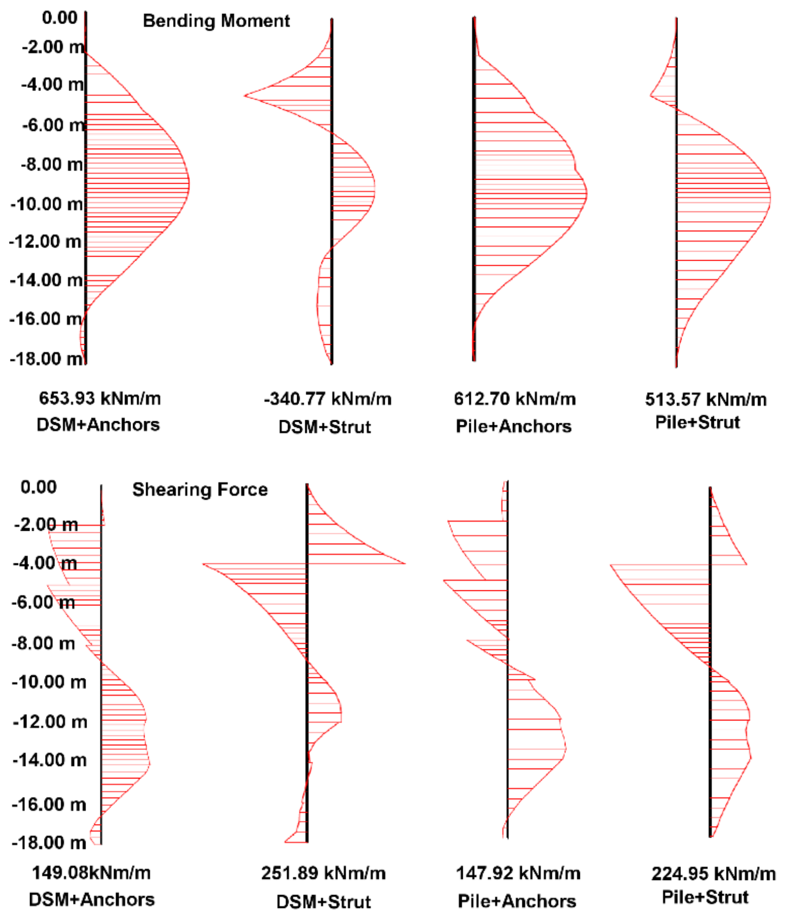

Fig. 4 Bending moment shearing force of the wall for each of the systems

Table 7 Magnitudes and results of bending moment and shear force of wall for different systems

System	DSM+ Anchor	Pile+ Anchor	DSM+ Strut	Pile+ Strut
Shear force(kN)	149	148	264	225
Bending moment (kN.m)	654	613	-356	514

After analysis of the proposed systems, it can be observed that in the back-braced supporting structure systems (anchorage), the bending moment and shear force of the walls decreased with increase of the wall stiffness. However, these variations are not significant (5% for bending moment and 1% for shear force). In fact, in back-braced systems, the bending moment and shear force of the excavation wall are highly dependent on the distribution of tensile force in the wall holding elements. Since the magnitude and intensity of forces in anchorage elements are higher in pile systems with anchorage (in comparison with DSM with anchorage), but their distribution along the wall length is more uniform, no significant difference can be observed. In front-bracing systems (struts), similar to back-bracing systems, the bending moment and shear forces are functions of compressive forces in the bracing element (struts). However, unlike with back-bracing systems, in these systems variations of bending moment are such that the bending moment magnitude will decrease by about 31% with decrease of the stiffness and increase of the walls' flexibility. In fact, this point verifies that the wall bending moment is only a function of the intensity and distribution of the forces induced in back- or front-bracing elements and hence does not directly depend on the wall stiffness. So, by increasing the force in the compressive constraints of struts and hence increasing the horizontal displacement fields at the back of the wall, in particular the free ends of the walls, the wall behavior and the curve of the bending moment and shear force will change along the wall. Therefore, strut compressive components with higher axial stiffness are required. Among the studied systems, tangent piles with struts induced a lower bending moment due to their high bending strength and therefore higher bending rigidity. Therefore, in this state, in comparison with tangent piles with anchorage, the value of bending moment reduced by 30%. Moreover, comparing the results clearly indicated that the induced bending moment of the walls depends on the stiffness of the bracing system and walls. Therefore, by means of the proper combination of these two factors, appropriate values for the supporting structure design can be achieved.

6. SUMMARY AND CONCLUSION

According to the results obtained and described in the corresponding sections, the conclusions of this research can be briefly summarized: One of the most important points of excavation design is the structures surrounding the excavated region and their degree of priority and strength. Therefore the best method, with the focus on the safest one, should be employed. The supporting structures of this study are among the most common and widely used methods of excavation support. According to the results obtained in this study, front-bracing methods (struts and secant piles) are proposed as the safest methods for fine-grained and manipulation-sensitive soils due to having the lowest amount of displacement. Deep soil mixing with anchorage (DSM-Anchor) is not recommended due to its low wall stiffness, which resulted in the highest level of displacement in fine-grained soils with a high groundwater level. According to the results obtained, it is suggested to increase the number of drilling steps to stabilize the cavity water pressure in fine-grained soils with a high underground water level according to the need for water pumping.

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