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INVESTIGATING THE INTERACTION BETWEEN STABILIZED EXCAVATION BY NAILING AND ADJACENT URBAN TUNNELS: CASE STUDY

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Urban development could be evaluated by considering the transportation and construction industries. The transportation industry development causes an increase in the urban subway lines as well as underground tunnels. Concerning the construction industry, the large-scale buildings development such as commercial malls, high-rise buildings, and underground parking structures may require deep excavations at metropolitan projects. In this paper, a parametric study is carried out by considering the distance of a tunnel from a retaining wall with the staged construction. PLAXIS 2.0D ver.8.5 software is used as an analysis tool. The results show that existing tunnels are affected more than retaining walls during an excavation when the structural response is considered. By increasing the horizontal distance of tunnel center from the wall, lateral displacement and the bending moment of the tunnel would decrease 14% and the vertical displacement and bending moment of tunnel's Crown would reduce by 15% and 12%, respectively. These interaction effects become negligible after a distance of 5 times the tunnel diameter. Besides, the existence of the tunnel in the vicinity of excavations would increase the top horizontal displacement of the retaining wall by about 13%. It is worthwhile to point out that the current paper is based on a case study on Sharif University multistory underground parking located near the subway tunnel in Tehran city stabilized by deploying a nailing and anchorage system.

Keywords: Subway tunnels, Deep excavation, Stabilization, Soil nailing, Staged construction, PLAXIS.

1 INTRODUCTION

In recent decades, the optimal usage of urban spaces by considering underground infrastructures has been incorporated into engineering studies. On one side, the increasing demand for high-rise building construction as residential or commercial buildings causing underground multistory parking and on the other side the development of public transportation networks like subway tunnels in densely populated cities have led to vicinity of both structures. Consequently, such nearness urges engineering assessment to evaluate the safety and serviceability of both structural systems in terms of structural interaction. Given the above facts, one of the major confronting issues would be the deep excavation involved during construction, which not only raises the risk of failure and fall of the excavated high walls as a serious threat to their adjacent structures but also affects the existing nearby subway tunnels. The main reason for such effect is the accompanying changes in the earth layers caused by the removal of soil mass that leads to the displacement of the tunnel floor and crown. Hence, excavating in the aforementioned areas and opting for the appropriate stabilization method attracts special attention. This research is attempting to carry out a parametric structural interaction analysis by altering the horizontal distance between the tunnel and the excavation.

2 RESEARCH BACKGROUND

According to researches, excavation in the vicinity of existing subway tunnels, which is inevitable due to the increasing demand for construction could cause adverse effects on them. Hence, ensuring the safety and integrity of both the tunnel structure and the adjacent excavation has become a major challenge for urban designers and geotechnical engineers Liang *et al*. (2017). A variety of construction methods have been developed to stabilize deep urban excavations such as side by side cast in situ anchored piles, soil nailed system with soldier piles utilizing rebar or pre-stressed strands, berm type retaining walls and anchored piles Lazarte *et al*. (2015). The selection of a typical retaining structural system for all projects is not feasible due to different parameters involved, i.e., variable geotechnical conditions and presence of a different range of surcharges due to the neighboring structures Farzi *et al*. (2018). Nowadays, in construction industry and urban areas, soil nail stabilizing method has gained popularity due to its technical suitability, ease of construction, relative free maintenance, top to down construction process, enough working space in front of excavation face, need for light machinery and equipment, appropriate performance during seismic events and deflections within tolerable limits (Alsubal *et al*. 2017, Ebrahimnezhad and Mojtahedi 2017). In the nailing method, bars serve as a reinforcement element to offset soil deformation. As the soil deforms, the nailing system not only distributes the force into the soil but also provides strength for the soil media in order not to slip, overturn or fail by developing the tensile force Shalmani and Cheshomi (2016). Since the unavoidable impact of deep excavations in soft soils and adjacent tunnels is very important, so the impact of this issue on line 1 of the Ningbo Metro Twin Tunnel has been analyzed with 3D numerical modeling by PLAXIS 3D. The research results indicate that adjacent excavation, surrounding soil, and twin tunnels affect each other. Based on such results, values of bending moments and displacements in the left tunnel closer to the excavation have increased. Besides, existing tunnels also cause displacement over soldier piles and surrounding soil as compared to the absence of the tunnel. Thus, the various stabilization methods were considered to reduce and alleviate the impact of the excavation on twin tunnels including the stage excavation, the soil continuum strengthening using separation walls. As a result, it was determined that values of bending moments and displacements of the left tunnel are directly related to the effects of loading and deformation of the surrounding soil, and this is considerably reduced by opting the stage excavation alternative more than other methods Sharma *et al*. (2001). Besides, the analysis of the tunnel response to the adjacent excavation, confirmed by field monitoring results, indicates that tunnel displacement remarkably decreases with increasing distance between the tunnel and the excavation Zhang *et al*. (2013).

3 RESEARCH ASSUMPTION AND CASE STUDY DEFINITION

The multi-story underground car park of the Sharif University is located at the north of Tehran's subway line 2. The parking excavation depth in the vicinity of the tunnel reaches the maximum height of 19 meters. The tunnel and the excavation are roughly aligned and at a distance of 16 meters apart. Since the NATM method is considered for tunnel construction and the short distance between the two structures, it is not possible to install nailing with a regular pattern. Hence for retaining the excavation, it is proposed to take advantage of piles, nails, and anchors simultaneously. Based on geotechnical investigation the soil around the tunnel is modeled with the fill material specification in the software. The surcharge load is considered 12 kN/m^2. In this research, PLAXIS software is used as a modeling tool. Mohr-Coulomb criterion is considered for plastic analysis. The stages of the excavation are applied in 3-meter steps. Different elements are used in modeling including the plate element for the tunnel lining, the pile element for the soldier piles, the anchor element for the anchored nails, the geo-grid element for the rebar nails and relevant anchorage zone. The vertical distance is 3 and 2 meters respectively between the rebar type nails and the anchored nails. The horizontal distance between both types of nails is 2 meters, as shown in Figure 1.

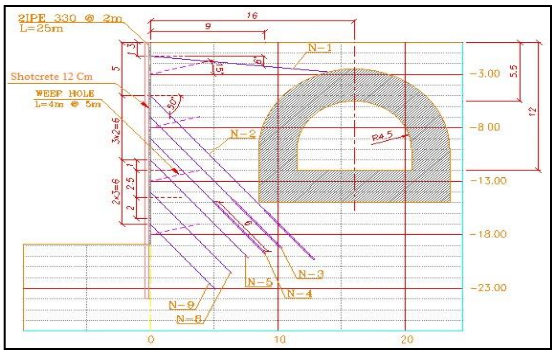


Figure 1. Typical section of the excavation of Sharif University Parking adjacent to the tunnel (case study).

Various material specifications considered for the soil, the nail, the anchored nail together with the geometrical and geotechnical parameters are presented in Tables 1 to 4.

Table 1. Soil geotechnical parameters.

Layer	°Φ	C (kPa)	E (kPa)
Fill Material	28	5	3×10^4
SC	37	5	8×10^4

Table 2. Geometrical specification.

Item	EA (kN)	EI (kN.m2)
Nail 40Ø	4.29e5	324
3 Multi strands anchor nail	84000	-
3 strands fixed anchor part	269800	-
Soldier piles (2 IPE 330)	2.63e6	4.94e4
Tunnel lining	1.039e7	1.386e5

Table 3. Nail parameters.

Item	Type	Size (m)	Distance (m)	Length (m)
N-1	Nail	40Ø	1	14
N-5	Nail	40Ø	2	12
N-8	Nail	40Ø	2	10
N-9	Nail	40Ø	2	8

Table 4. Anchored nail parameters.

Item	Strand No.	Distance (m)	Size (m)	Length (m)	Free Length (m)	Fixed Anchor Length (m)
N-2	4	2	60	21	14	6
N-3	4	2	60	17	10	6
N-4	4	2	60	15	8	6

4 SUBJECT DEFINITION AND MODELING

In this research, a numerical analysis is carried out to model the interaction of the deep excavation against the underground tunnel. To perform the analysis, 7 parametric models have been developed with the assumption of plane strain conditions by using the finite element software plaxis2D ver. 8.5. Since each of these 7 models contains 16 analytical construction steps, a total of 112 soil plastic analyses have been conducted. This parametric analysis involves changing the tunnel center distance from the excavation wall considering the tunnel diameter ratio. Those parameters for measurement evaluation include top horizontal displacement and vertical bottom displacement of soil-nailed retaining wall, bending moment and vertical displacement of the tunnel crown and horizontal displacement of the sidewall of the tunnel. The overall dimensions of soil media and the measuring parameters are presented in Figures 2 and 3.

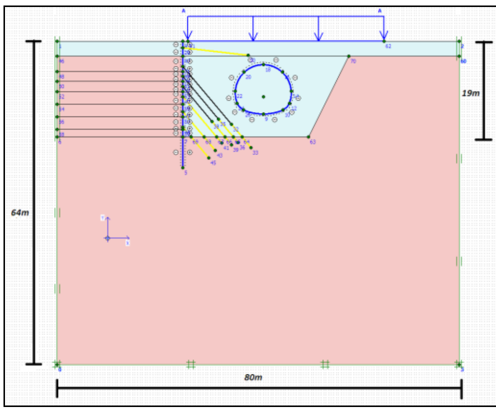


Figure 2. The model dimensions in PLAXIS.

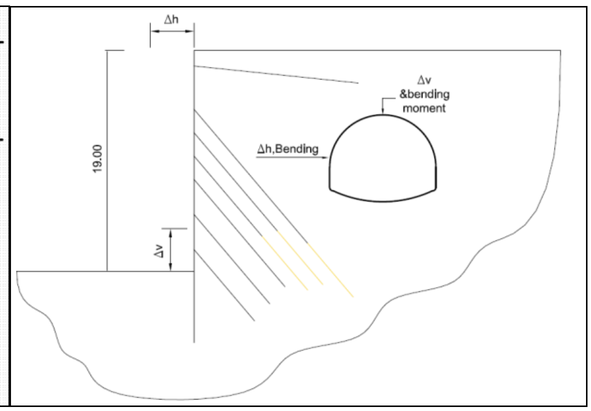


Figure 3. The measured parameters in PLAXIS.

5 PARAMETRIC ANALYSIS

After setting out the base model, the parametric analysis of the tunnel and excavation interaction is performed by changing the tunnel distance from the excavation with 5-meter steps equal to half the tunnel diameter in the horizontal direction, as shown in Figure 4.

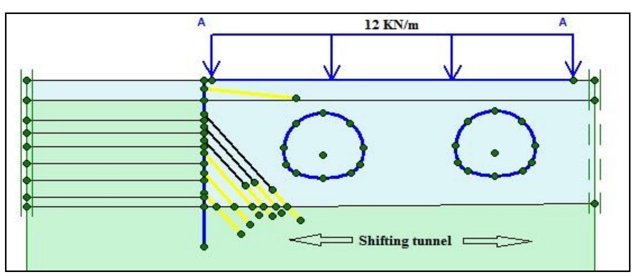
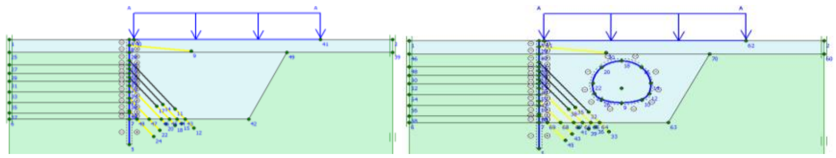


Figure 4. The tunnel's location at a different distance to the excavation in PLAXIS.

In the outset a model is set out in which there exists no tunnel then the tunnel is placed according to the case study technical specification. Both models with tunnels and without tunnels are considered as two extreme states. As an illustration, in all models, the dimension of soil continuum and all soil mechanical parameters are kept the same so that the results can be compared, as shown in Figure 5.



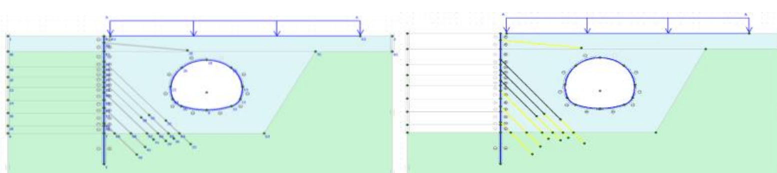
(a) (b)

Figure 5. The extreme states models in PLAXIS, (a) no tunnel; (b) just tunnel is active.

6 STAGE CONSTRUCTION

Since the staged excavation is a fundamental principle for the construction, so it is applied to all analytical models in PLAXIS software. Consequently, each model contains 16 stages of construction. The steps of modeling are listed below and 2 of them are shown in Figure 6.

a Activating the tunnel, applying surcharge load, and activating the excavation wall
b, c Stage 1 of excavation and activating the first row of nails
d, e Stage 2 of excavation and activating the first anchor and applying pre-stress force
f, g Stage 3 of excavation and activating the second anchor and applying pre-stress force
h, i Stage 4 of excavation and activating the third anchor and applying pre-stress force
j, k Stage 5 of excavation and activating the second row of nails
l, m Stage 6 of excavation and activating the third row of nails
n, o Stage 7 of excavation and activating the fourth row of nails
p Stage 8 of excavation



(a) (b)

Figure 6. Construction Stages, (a) the first stage, (b) the 16th stage.

7 PARAMETRIC ANALYSIS RESULTS

The results of the parametric analysis in terms of measuring parameters versus distance ratio are presented in Table 5.

Table 5. The parametric analysis results of the interaction between excavation and tunnel (T).

Distance (Divided by diameter)	Moment T Wall (kN.m)	ΔH T Wall (mm)	Moment T Crown (kN.m)	ΔV T Crown (mm)	ΔH Retaining Wall (mm)	ΔV Retaining Wall (mm)	Note
0	0	0	0	0	20	10	No tunnel
1.5	391.92	42.58	329.32	13	39	15	Dist.: 16 m
2	304.15	35.50	280.70	8.1	35	7	Dist.: 21 m
2.5	258.64	28.50	244.58	5.2	33	10	Dist.: 26 m
3	223.36	24.11	219.96	4.1	26	4.6	Dist.: 31 m
3.5	199.32	20.78	200.39	6	23	4.2	Dist.: 36 m
4	180.77	19.35	177.67	4.3	21	6	Dist.: 41 m
0	162.60	11.80	146.77	0	0	0	Just Tunnel

According to the above results, as the distance between the tunnel and excavation increases so the unfavorable effect of measuring parameters and internal forces such as the bending moment of the tunnel wall and crown, the vertical and horizontal deformation of the retaining wall and tunnel decrease. In fact, the interaction of these two structures gradually declines until it becomes negligible at a distance of 4D.

8 CONCLUSION

(i) As the first hypothesis of interaction, the tunnel structure will get more affected from deep excavation than the retaining structure from the tunnel existence.

(ii) The existence of a tunnel during the deep excavation process causes a 13% increase in top horizontal displacement of the retaining wall compared to the absence of a tunnel.

(iii) The existence of a tunnel during the deep excavation increases the vertical displacement of the soil in the vicinity of the bottom of the retaining wall by 8%. This issue is also evaluated to happen due to the change of peripheral conditions of the soil and the change in the distribution of stresses and internal strains.

(iv) By increasing the horizontal distance of the tunnel center from the excavation, the vertical displacement of the tunnel crown decreases. The average reduction is about 15%. In other words, in the vicinity of the tunnel, the cracks in the tunnel lining are expected.

(v) By increasing the horizontal distance of the tunnel center from the excavation wall, the tunnel crown bending moment decreases by an average rate of 12%, and this effect would be omitted by about 5 times the diameter of the tunnel.

(vi) By increasing the horizontal distance of the center of the tunnel from the excavation wall, the horizontal displacement and the bending moment of the tunnel wall decrease by 14%, i.e., with the excavation near the tunnel, the risk of cracks in the tunnel wall escalates.

(vii) Should the horizontal distance between the center of the tunnel and the retaining wall exceeds 5 times the tunnel diameter, the interaction of these structures would disappear. Therefore, the interaction assessment for distances below such limit is recommended.

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