Performance analysis of a soil nail wall of a deep excavation

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ABSTRACT
This study surveys the performance of a temporary soil nail wall with maximum height of 30.6m in Amirkabir complex project, located in Tehran. The water table located 15m under natural ground surface. Numerical models were developed using a Finite Element software, based on results of field and laboratory tests. Simulation construction process of the soil nailed wall was carried out considering the sequence of construction stages. The modeling results were analyzed and compared with the in-situ monitored data. The results demonstrate, the model's horizontal deformations are generally greater than in-situ monitored values. Therefore the parameters of soil layers were back analyzed to narrow the differences between the results of models and monitored data. As it was an EPC project, the results of monitoring and back analysis are applied to optimize system design during construction.

RÉSUMÉ
Cette étude examine la performance d'un mur de clou de sol temporaire avec une hauteur maximale de 30,6 m en Amirkabir projet complexe, situé à Téhéran. La nappe phréatique située 15m sous la surface de sol naturel. Certains modèles numériques ont été développés à l'aide d'un logiciel Finit Élément, basé sur les résultats des examines sur le terrain et en laboratoire. Processus de construction de la simulation de la paroi clouée du sol a été réalisé compte tenu de la séquence des étapes de construction. Les résultats de la modélisation ont été analysés et comparées avec les données in-situ surveillés. Les résultats démontrent, les déformations horizontales du modèle sont généralement supérieures aux valeurs surveillées sur place. Par conséquent, les paramètres de couches de sol ont été de nouveau analysés pour conformer les résultats des modèles et des données surveillées. Comme il était un projet de l'EPC, les résultats de la surveillance et à l'arrière-analyse sont appliquées afin d'optimiser la conception du système en cours de construction.

1 INTRODUCTION

During the past recent years, due to the demand for the construction of high-rise structures and the need for obtaining enough parking spaces, soil nailing system extensively employed within Tehran as temporary and permanent retaining walls, to allow great numbers of basements below these structures.

Soil nailing is an in-situ earth reinforcement method which enables an earth mass to achieve a state of self-support through the introduction of driven or grouted steel bars into the mass during excavation and exposure.

Prefabricated drainage elements are placed at designed spacing during the excavation and construction of soil nailed wall.

The design process and the results of the performance of temporary soil nailing system in Amirkabir Commercial project, height of excavation reaching to about 30.6 meters, is compiled in this study.

The applied steel nail bars are of 25 to 32 millimeters in diameter and 6 to 14 meters in length. The vertical spacing of soil nails are 1.5 and 2.0 meters, while the predrilled holes have diameter of 101 millimeters and an inclination of 15º. Construction method, soil geotechnical properties, and the soil nails and the shotcrete characteristics are briefly discussed.

The performance of the walls is monitored by Laser Total Station recordings taken at certain intervals in parallel to the excavation progress.

Within the next sections, the hunts are on for the comparison the FE modeling outputs to the achieved results from the in-site persistent detailed monitoring of the eastern wall of Amirkabir project, and explanation of back-analyze and the FE modeling and improvement of the soil nailing system.

2 PROJECT GENERAL SPECIFICATIONS

Amirkabir project site is located near Tajrish Square in the north of Tehran. The complex has been constructed in a land with about 11000 m² space area.

Conventional excavation support systems were originally studied to support these cuts. However, given the large potential spans, an internally braced system was found not to be feasible. Therefore, soil nail system and soldier pile system were considered.

The soil nail and shotcrete system consisted of approximately 48000 meters soil nails, and 11800 m² of wall surface.

The total volume of excavation is about 260000 bank cubic meters. Figure 1 illustrates the north-east view of the project site.

Figure 1. The north-east view of the project site

Some 3 to 6 floor residential buildings locate in the south and west of the project site. The crowded Maleki Street abuts the project site to the north and east.

The original site topography slopes from the NW to the NE of the project site area.

The top elevation (EL) of NW and NE is 1002.0 and 991.0, respectively. However the excavation was performed to EL 971.4. At the deepest cut point, the proposed structure cuts into the original slope, resulting in a total cut of 30.6 m at the NW corner to reach the lowest basement level. Figure 2 shows the plan view of the project site.

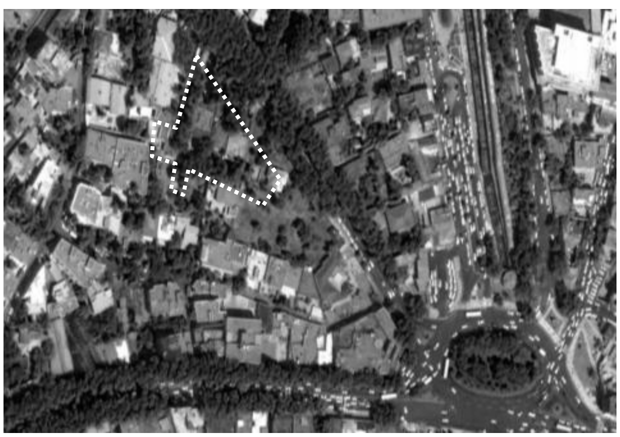

Figure 2. The plan of the project site

2.1 Geotechnical Conditions

Comprehensive geotechnical investigations were performed to provide required data for the design procedure.

A total number of 5 boreholes and 5 test pits were drilled within the project site. The investigations were tailored to characterize the soil condition of the project site.

SPT, Sand-cone density test, plate load test, the patent test of 'Loading at the edge of the trench' and the routine soil property tests were conducted.

In the investigations, the water table was observed in the test pits at the level of 987 m.

According to the obtained geotechnical data, several geological layers are considered within design procedure of the support of excavation system. The stratigraphy, thickness of each layer, and range of soil properties are presented in Table 1. Within the table, 'E' stands for the vertical Modulus of Elasticity, 'C' stands for the cohesion, 'φ' stands for the internal friction angle and 'γ' stands for the moist density.

Table 1. Arrangement of performed Soil nails-Y1 wall

Soil layer	Thickness [m]	φ [°]	C [kPa]	γ [kN/m3]	E [MPa]
Layer1	3	26	20	17	200
Layer2	3	34	15	19	300
Layer3	7	38	25	20	800
Layer4	21	38	20	22	800
Layer5	-	32	35	19.5	700

The permeability values were applied within the FE PLAXIS numerical seepage analyses in order to design the length and inclination of the required drains and the required geotextile strips' configurations.

The vertical and horizontal coefficients of permeability were assessed by summarizing the laboratory and in-situ Lufran permeability test results. The obtained coefficient of permeability from the constant head and falling head Lufran tests are in the range of 7.9E-7 to 9.4E-5 cm/s and 1.0E-5 to 1.4E-4 cm/s respectively. Furthermore, the obtained coefficients of permeability, from the laboratory constant and falling head permeability tests, are in the range of 7.1E-3 to 5.8E-2 cm/s and 1.8E-8 to 9.5E-7 cm/s respectively.

3 DESIGN AND ANALYSES-INITIAL DESIGN

For the North wall, the critical design profiles are Type A. The profile consisted of a cut from the top elevation EL 1002.0 to EL 971.4 m.

The soil nail wall initial design for the Type A consisted of 17 rows of nails, while the vertical and the horizontal spacing vary between 1 to 2.0 meters depending on the design's specifications. Table2 and Figure 3 present the soil nail patterns for the initial design.

Diameter of nails vary from 25 to 40-mm (#25, #32 and #40). AIII bars inclined at 10 to 15 [deg] angles, except the nails of the first two row which were in diameter of 25-mm and five terminal row which were in diameter of 40-mm.

The excavation was proceeded in staged pattern. Each lift had a height of about 2-m and a width of 6-m. The free face was immediately covered with a 10-cm thick layer of temporary facing. Temporary facing consisted of shotcrete and cold-drawn steel welded wire mesh (WWM).

Given that the excavation was surrounded by water from the approximate elevation of 987.0 m, the potential of high water inflow was a major concern. To prevent water pressure from developing behind the wall facing, inclined four inch drains are accompanied with vertical geocomposite strips of 30 cm width installed from the EL 988.0.

Table 2. Soil nails pattern-Initial design

Row	Level [m]	Horizontal spaces [m]	Length [m]
1	1000.5	2	8
2	999.0	2	12
3	997.0	2	12
4	995.0	2	12
5	993.0	2	14
6	991.0	1.5	16
7	989.0	1.5	18
8	987.0	1.5	18
9	985.0	1.5	20
10	983.5	1.5	20
11	982.0	1.25	18
12	980.5	1.25	16
13	979.0	1.25	16
14	977.5	1	14
15	976.0	1	14
16	974.5	1	12
17	973.0	1	12

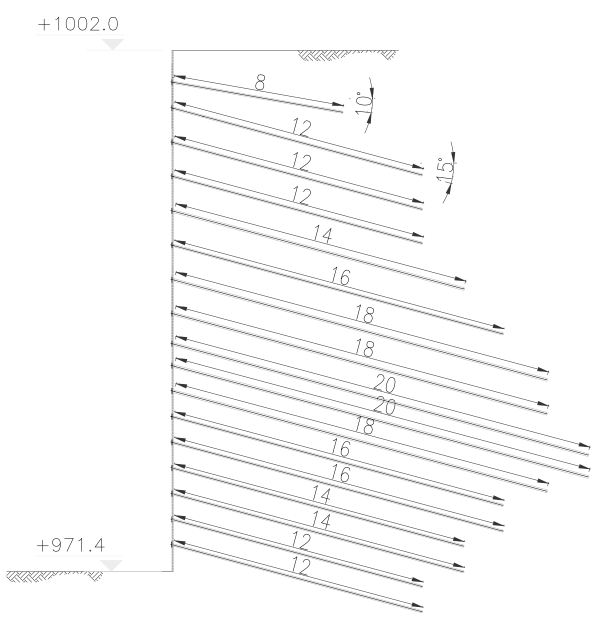

Figure 3 .Initial design Soil Nailing Pattern-Type A

Drains, in length of 4 to 6 m, were implemented at 2.5 meter horizontal spacing's with an inclination of 10° to the horizontal. The typical vertical spacing was 3 meters.

The drainage system also included a footing drain and weep holes to convey collected drainage water away from the wall face. A number of temporary open sumps and trenches were excavated during the construction procedure which included five submerged water pumps.

4 IN-SITU PERFORMANCE MONITORING

An instrumentation program was established to monitor the performance of the soil nail system and to provide early detection of deflections that could potentially damage the nearby structures.

Several displacement reference points (reflectors) were placed at various locations at the EL. +1001 m to measure the horizontal movements. The location of the reflectors is illustrated in Figure 4. The reference points were monitored using a Laser Total Station.

In addition to the instrumentation, daily visual surveys were performed during the course of the excavation to check for cracking of shotcrete and the inevitable cracking of the adjacent structures.

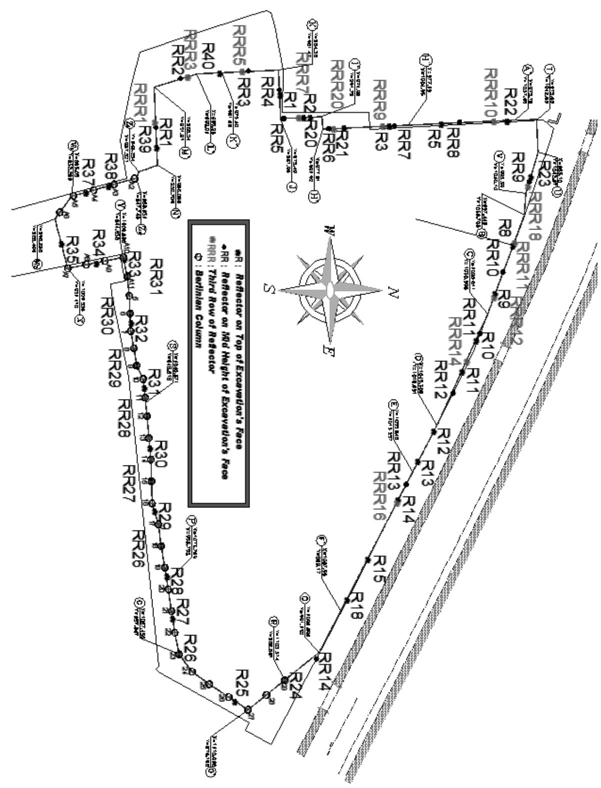

Figure 4. The location of the reference points

5 INITE ELEMENT MODELING-INITIAL DESIGN

5.1 Input parameters

The soil nail wall system was numerically simulated using a two-dimensional finite element code PLAXIS, mainly to provide information for the performance of the soil nail wall. Simulation of the entire soil nail wall construction process was carried out in a sequence of construction stages. In each construction stage a sufficient number of calculation steps were used to obtain an equilibrium state.

The elastic perfectly-plastic Mohr-Coulomb (M-C) constitutive law was used to model the native soil, and for the nails and facing elements an elastic model was used.

The soil parameters were considered constant in each layer. The plane strain mesh was defined by 15-node triangular elements with 12 Gaussian points. Pore pressure distributions were generated based on phreatic level and the steady-state groundwater calculation.

Shotcrete wall of 10 cm thickness with reinforced wire mesh, was modeled as Plate elements of EA=3×106 kN/m and EI=2500 kN/m2/m. Soil nails were modeled as geotextile elements of E=2.1×108 kN/m2 (Gysi et al. 2002). However, scaling was applied in input parameter definitions in order to average the effect of three-dimensional problem to a two dimensional problem (Itasca. 1999). Interface elements were used to model the stick-slip interaction between the soil nails and the native soil. An elastic-plastic model was used to describe the behavior of interfaces for the modeling of soil-structure interaction.

5.2 Outputs

The results of modeling of the initial are presented within this section. Figure 5 shows the calculated horizontal displacement shadings.

The value of the extreme horizontal displacement at the location of the installed reference points (EL. +1001 m) for type A is 207.8 mm.

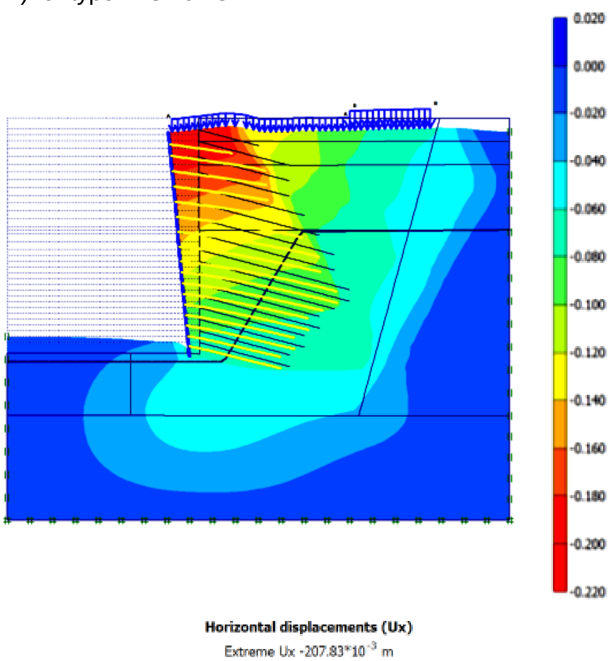

Figure 5. The horizontal displacement shadings after Construction [m]

Figure 6 illustrates the variation of the calculated horizontal displacements at the location of the reference points, against the excavated height for all types.

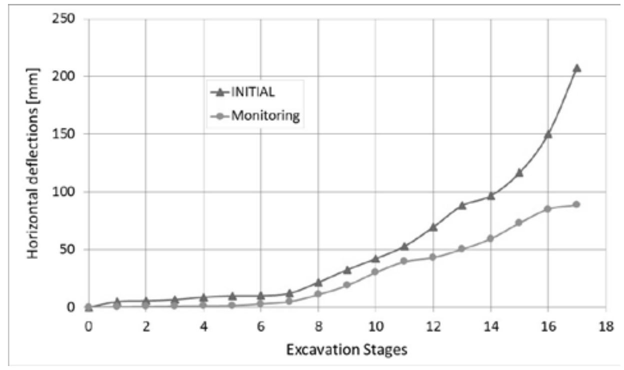

Figure 6. The variation of the calculated horizontal displacements vs. excavated height

6 BACK ANALYSIS

After construction of 5 stages of soil nailing system and reaching to EL. +992.0 m, the modeling results were analyzed and compared with the in-situ monitored data. The results demonstrate, the model's horizontal deformations are generally greater than in-situ monitored values.

As it is shown in the figure 6, the resulted lateral deformation at the elevation of the reference points is about 9.96 mm, soon after accomplishment of stage 5.The monitoring data, soon after accomplishment of stage 5, indicates that the maximum lateral deflection of the reference points was about 1.5mm.

To decrease the differences between models and monitored results, design approaches have been revised. The approach that advised by Singh et al. (2009) to model soil nailing system using Plaxis program was applied.

The 15 node triangular element type was selected for the mesh used in the FE model. The soil was modeled using the Hardening-Soil model (Schanz et al. 1999).

Plate elements were used to model the nails and the facing. However, no interface element was introduced between the soil and Plate elements. The soil nails were simulated with equivalent Plates using elastoplastic Plate elements. The shotcrete wall was modeled using elastic Plate elements and fixed connection was used between the wall and the nails. Plate elements parameters are summarized in Table 3.

Table 3. Plate elements parameters

υ	Weight [kg/m/m]	EI [kN/m2/m]	EA [kN/m]	Identification
0.20	143	344	7.37E4	Soil Nail
0.18	239	39651	2.73E6	Shotcrete

The new model with revised modeling approaches resulted 6.64mm horizontal deformation at elevation of the reference point after accomplishment of stage 5.

To more decrease the differences between models and monitored results, soil parameters have been back analyzed.

By 100% increment of Young's modulus E associated with an increment of 10 [kN/m^2] in soil cohesion, the horizontal deformation resulted by model have equalled to 5.41 mm. while, just by 100% increment of Young's modulus E this value was 6.64 m.

7 FINAL DESIGN

To make the soil nail system more economic, the design has been revised and length of the soil nails have been decreased for stage 7 to 17. The new model with the revised soil parameters and design approaches has used to revise the soil nailing system design. Considering the monitoring results, these revisions have been done stage by stage during the wall constructions.

The soil nail wall final design for the Type A consisted of 17 rows of nails, while the vertical and the horizontal spacing vary between 1 to 2.5 meters depending on the design's specifications. Table 4 and Figure 7 present the soil nail pattern for the final design.

Table 4. Soil nails pattern-Final design

Row	Level [m]	horizontal spaces [m]	Length [m]
1	1000.5	2	8
2	999.0	2	12
3	997.0	2	12
4	995.0	2	12
5	993.0	2	14
6	991.0	2	14
7	989.0	1.5	14
8	987.0	1.5	14
9	985.0	1.5	12
10	983.5	1.5	12
11	982.0	1.5	14
12	980.5	1.5	12
13	979.0	1.5	10
14	977.5	1.5	8
15	976.0	1.5	8
16	974.5	1	6
17	973.0	1	6

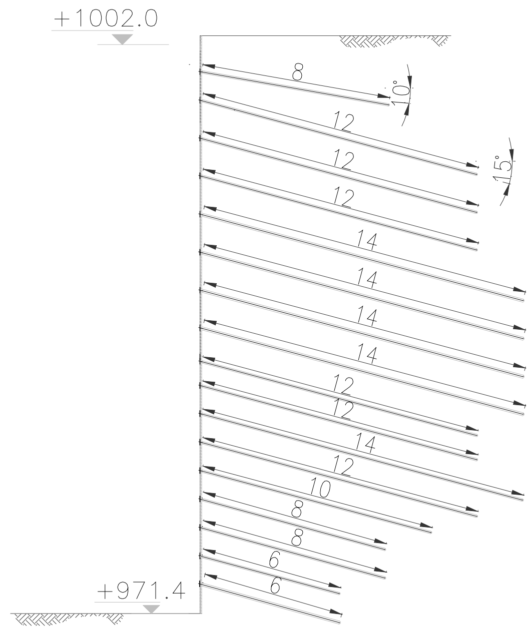

Figure 7. Final Design Soil Nailing Pattern-Type A

Figure 8 shows the calculated horizontal displacement shadings for the final design.

The value of the extreme horizontal displacement at the location of the installed reference points (EL. +1001) for type A is 94.98mm.

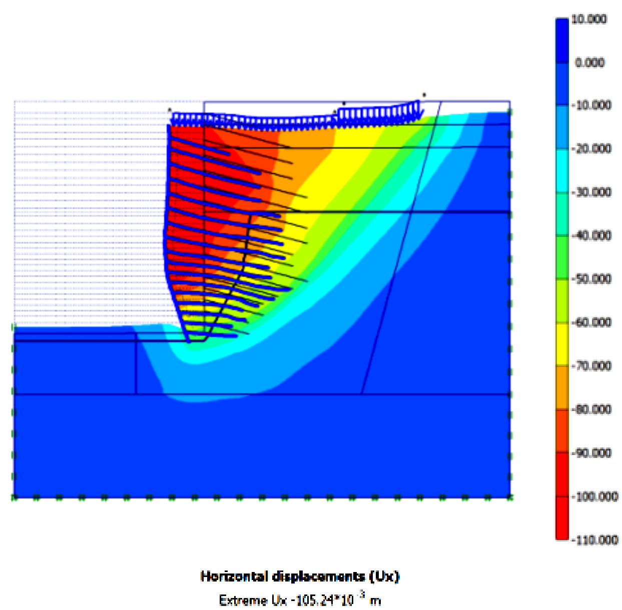

Figure 8. The horizontal displacement shadings after Construction-Final Design [m*10^{-3}]

8 MONITORING RESULTS

The maximum measured value of the average cumulative horizontal displacement on the project occurred along the

north part of the east wall, where the measured maximum horizontal movement was approximately 97.5 mm.
Recommendations of FHWA suggest horizontal deflections of 0.005 H, as an upper limit of acceptable performance during construction.

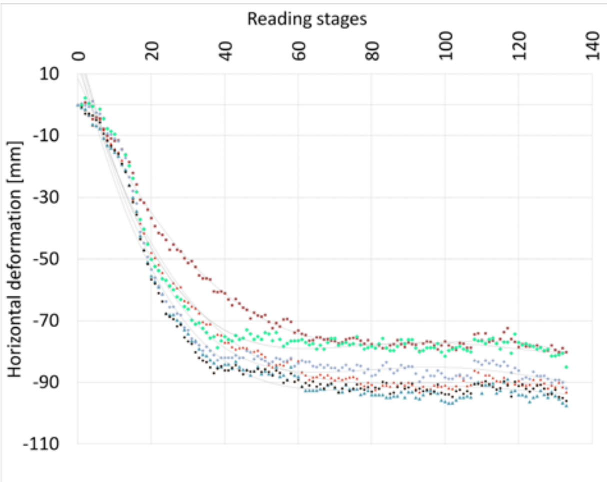

Figure 9. Monitored horizontal displacement trend of the soil-nailed wall

As shown in Figure 9, maximum measured horizontal deformation of the wall was lower than 0.005H that suggested by FHWA as an upper limit of acceptable performance.
The mean cumulative horizontal displacement for the Type A is 9.5 cm that it coincides with the results of the revised model. Figure 10 illustrates polynomial regression of predicted and measured values of horizontal displacements at the level of the reference points for the side walls.

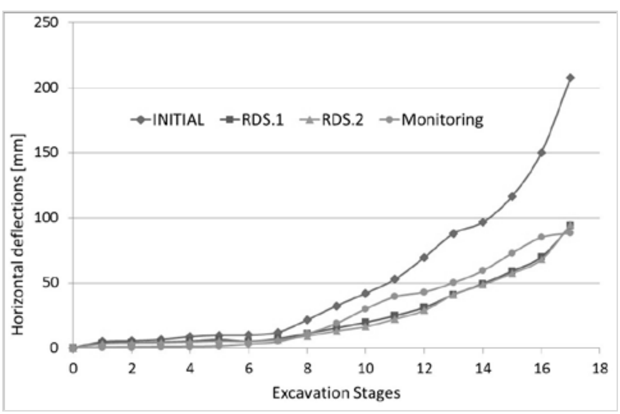

Figure 10. The polynomial trend of the mean predicted and measured horizontal displacements against the construction stage

9 CONCLUSION

This case study on design and performance of the excavation for Amirkabir Commercial indicates that concurrent using the monitoring data and numerical FE analyses to improve an initial design for soil nailing system can be very useful and practical tools to reach an economic and effective design.

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