Assessing the functionality of different constitutive models in predicting the behavior of deep stabilized excavations

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ABSTRACT

In this study, application of Limit Equilibrium (LE) and Finite Element Model (FEM) analyses have been presented and discussed for support design of a 30-m deep excavation in Tehran. A combination of nailing and strand anchorage with block system were designed and used to support the vertical cut in multiple steps of excavation. In this regard, safety factors have been assessed based on LEM using Mohr-Coulomb model, while deformations were estimated using the Hardening Soil model in an FEM platform. Comparison of the design models and field monitoring of deformations indicate a reasonably well performed engineering approach which can be implemented in similar projects in dense urban areas.

Keywords: Deep excavation; anchored wall; constitutive model; sliding; deformation; field monitoring

1 INTRODUCTION

In recent years, the number of deep excavations in metropolitan areas has increased dramatically. Observation of the safety requirements in these projects are very important and designers are always seeking to reduce the occurrence of catastrophic events by accurately predicting soil behavior. In general, in designing stabilized excavations in urban areas, two important factors for safety control should be considered: (1) the safety factor against general sliding; and (2) the control of the displacements of the stabilized wall (Puller; 2003 and Ou; 2014). In order to control the aforementioned factors, accurate information must be provided on the mechanical properties of soil and, in addition, a proper constitutive model for predicting soil behavior should be selected.

In this research, a case study on a deep excavation project in Tehran (namely Mojdeh project with a depth of excavation of about 30 m below the ground surface) has been carried out and the functionality of different constitutive models on predicting the safety parameters has been investigated. For this purpose, two constitutive stress-strain models, namely linear elastic and nonlinear hardening models have been considered to assess the deformation behavior of the stabilized walls. In addition, two shear failure criteria, namely Mohr-Coulomb and Hardening Soil models have been selected to assess the factor of safety against the general sliding of the stabilized system. In this regard, 2D finite element model (FEM) simulations and 2D limit equilibrium (LE) analyses have been conducted, respectively. It is noted that to stabilize the walls, pre-stressed anchors have been implemented in conjunction with steel soldier piles (Jafarzadeh and Garakani; 2016).

2 EXCAVATION CHARACTERSTICS AND GEOTECHNICAL SITE INVESTIGATION

A vertical open excavation was planned to be carried out in a dense urban area in Tehran at a maximum depth of almost 30 meters below the existing ground surface. One of the major complexities in the project was presence of various buildings adjacent to the edge of the vertical cut which required the engineering team to take into account their applied surcharge, and also to control deformations to comply with maximum building foundation deformations specified in Iranian codes, the intricacy of which was doubled as the site was surrounded by some older buildings less tolerant to uneven settlement and deformations.

Based on the fact that deformations had to be limited around the adjacent building foundations, a combination of soil nailing and strand anchorage with block system was selected as the best engineering practice for this project. At shallow depth where tensioning the anchor system could potentially result in considerable deformations just below building foundations, soil nailing was used up to depths of approximately 6 meters. However, to provide enough lateral support to keep the deep vertical cut stable, anchors were installed at deeper elevations.

Geotechnical site investigation was carried out and soil parameters were either directly measured or estimated based on engineering judgment. Specifically, large scale direct shear and plate load tests were performed at various depths to determine the soil layering and required shear strength and stiffness parameters at various depths. Shear strength and stiffness parameters were of particular interest for the purpose of numerical simulations.

As previously noted, Mohr-Coulomb the Hardening Soil model (Schanz and Vermeer, 1998) were used for stability and deformation analyses in LE and FEM platforms, respectively. The Hardening Soil model also takes advantage of the Mohr-Coulomb failure criterion, which does not require estimation of more input parameters for deformation analysis. A summary of soil layering at the site together with estimated input parameters used in both LE and FEM analyses is presented in Table 1. The groundwater table was also measured to be horizontal at a depth of -22 m measured from the average ground surface.

Table 1. Summary of soil layering and input soil parameters.

Depth [m]	0-7	7-10	10-15	15-20	Below 20
Soil Type	GW-GC	GW-GC	SW	GW-GC	GC
Moisture Content [%]	7.1	3.7	8.9	4.5	15.3
γ_{wet} [kN/m^3]	18.8	21.1	19.1	19.5	18.1
c' [kN/m^2]	19	2	7	52	37
ϕ' [degrees]	33.0	36.0	30.8	37.3	33.7
E_{oed}^{ref} [kg/cm^2]	365	420	360	450	250
E_{50}^{ref} [kg/cm^2]	365	420	360	450	250
E_{ur}^{ref} [kg/cm^2]	1530	1245	1355	1160	1035
ν [-]	0.2	0.2	0.2	0.2	0.2

3 SLOPE STABILITY AND DEFORMATION ANALYSES

Slope stability analyses were carried out to calculate the safety factor (SF) against failure (LE analysis) using Slope/W software. An advantage of this platform is the option of separately modelling nailing and anchor elements in which the maximum tensile strength and locking forces can be defined, respectively. State-of-the-art slope stability methods such as Bishop, Janbu and Morgenstern-Price were implemented and the minimum SF values obtained for the walls at each side of the excavation were determined. In fact, various soil nails and anchor tensioning forces were examined by trial and error to establish an optimum design to satisfy the minimum SF of 1.5 as per the Iranian code and engineering common practice. It has to be mentioned that initially, the critical slipping surface were determined for each excavation wall with no support and the length of soil nails and anchors were determined to extend past the unsupported failure surface. An example of the LE analyses carried out for one of the excavation walls is shown in Figure 1.

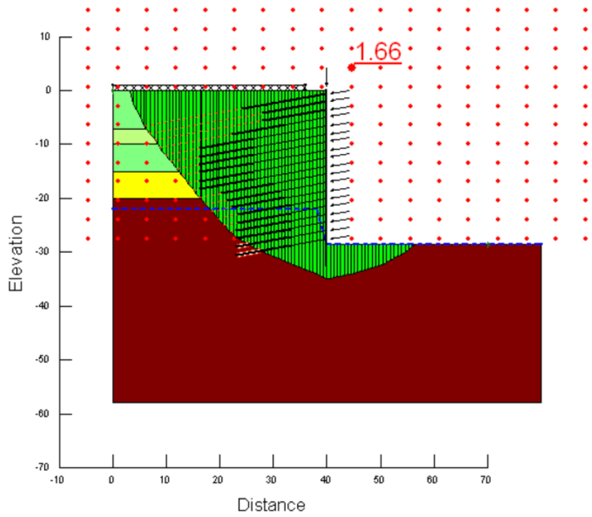

Fig. 1. Typical slope stability analysis (LE) using Slope/W

FEM analyses were also undertaken to assure that settlements and lateral deformations are within the specifications, specifically for those walls being excavated underneath the existing building foundations. To do so, staged construction of the excavation was modeled in Plaxis software with the Hardening Soil model being used. Maximum deformations were limited to 2.5 cm at the top of each side wall. The failure criteria used for design of the anchorage and block system included the following:

- tensile failure of tendon,
- pullout failure of grout/ground bond,
- pullout failure of tendon/ground bond,
- external failure mode,
- internal failure mode,
- facing failure mode.

To determine the bond length for anchors, a safety factor of 1.75 was applied. Output figures for FEM analyses of a selected excavation wall are shown in Figures 2, 3, 4 and 5, showing the horizontal and vertical effective stresses, the deformed mesh, and deformation arrows, respectively.

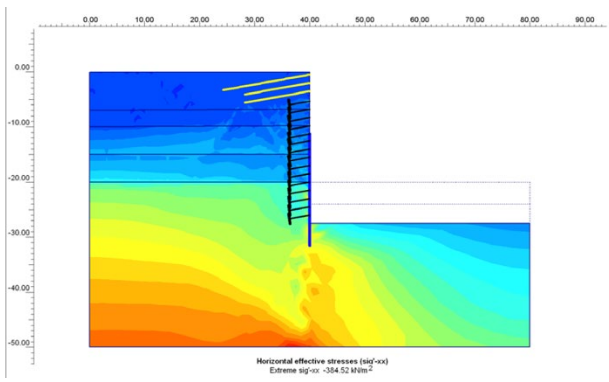

Fig. 2. Horizontal effective stress contours (after excavation)

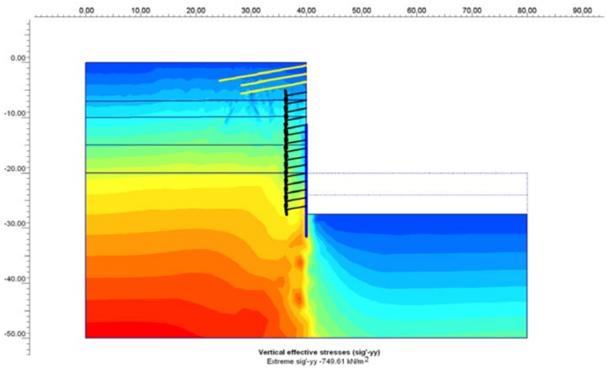

Fig. 3. Vertical effective stress contours (after excavation)

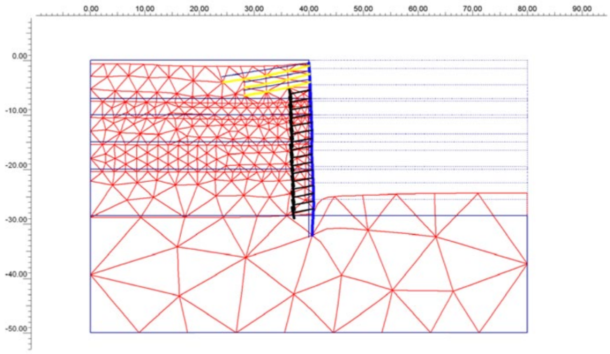

Fig. 4. Deformed mesh (exaggerated)

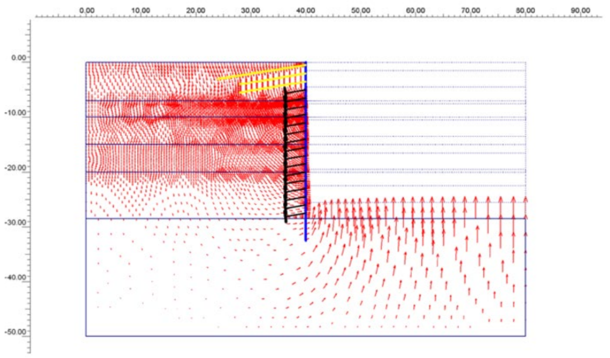

Fig. 5. Deformation arrows (after excavation) – maximum 1.6 cm

4 FIELD MONITORING AND ASSESSMENT OF MODEL PERFORMANCE

Following the initial design, excavations started in stages. At each stage, 3 m of soil was removed along each wall followed by installation of top soil nails and anchors (Figures 6, 7 & 8). Deformations at various elevations on each wall was constantly monitored. It was observed that maximum monitored deformations were limited to 1/2 to 2/3 of those obtained from numerical models. This suggests that the design was carried out conservatively to some extent, which can be attributed to uncertainties resulting from estimation of soil parameters, limitations of the constitutive soil model used, and the methods used in Plaxis for modeling soil nails and anchors.

Fig. 6. East wall of the project.

Fig. 7. South wall of the project.

Fig. 8. West wall of the project.

3 CONCLUSION

In the present study, an approach for the design of mechanical support for deep excavations in urban areas is presented for a real case study completed in Tehran. LE and FEM analyses were carried out as a part of the design and continuous monitoring was done during excavation stages to assure the performance of the model. It was observed that within the LE and FEM platforms, Mohr-Coulomb and Hardening Soil models give adequate results comparable to those monitored at the site. Uncertainties resulting in a relatively conservative design were assess to arise from estimation of soil parameters and the elements used in the software for modeling soil nails and anchors.

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