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STABILITY ANALYSIS OF A SHALLOW DEPTH METRO TUNNEL: A NUMERICAL APPROACH

ANALIZA STABILNOŚCI PŁYTKIEGO TUNELU METRA Z WYKORZYSTANIEM METOD NUMERYCZNYCH

In this paper, an attempt has been made to use numerical modelling for simulating a long halt in construction process at a shallow depth metro tunnel and investigate the effects of soil nailing to increase the tunnel face strength. Finite difference software FLAC with high applicability in a continuum environment was adopted for this study. The tunnel is being excavated for Tehran metro project. Shield tunnelling with roadheader and back hoe cutting tools is applied in the excavation process. Mohr-Coulomb elasto-plastic constitutive law is considered to model the ground. After two months halting in excavation process, tunnel instability and ground subsidence were recorded in thirteen different monitoring points. Numerical simulation results showed a close approximation (11-16%) between measured and FLAC computed displacements of the tunnel crown in case of unsupported face, which is in close proximity and a proof indicates the reliability of simulation. Also, simulation results exhibit a significant reduction in the ground subsidence and tunnel instability in case of supported face by means of the soil nailing.

Keywords: Numerical modelling, Soil nailing, Shield tunnelling, Subsidence

W artykule podjęto próbę wykorzystanie metod modelowania numerycznego dla potrzeb symulacji dłuższego przestoju prac związanych z budową płytkiego tunelu metra w celu zbadania skutków wzmacniania gruntu dla zwiększenia wytrzymałości tunelu w części czołowej. W badaniach zastosowano oprogramowanie wykorzystujące metodę różnic skończonych FLAC, do zastosowań w środowisku ciągłym. Wykop tunelu wykonywany jest w ramach budowy metra w Teheranie. Kopanie tunelu odbywa się przy pomocy urządzeń tarczowych do drążenia tuneli oraz urządzeń podsiębiernych do urabiania. Do modelowania gruntu zastosowano model sprężysto-plastyczny Mohra-Coulomba z wykorzystaniem równania konstytutywnego. Po dwumiesięcznym przestoju w pracach budowlanych, zarejestrowano wielkości niestabilności tunelu oraz osiadania gruntu w trzynastu równych punktach pomiarowych. Wyniki symulacji numerycznych wykazały wysoką zbieżność (11-16%) pomiędzy wartościami zmierzonymi a przemiesz-

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czeniami obliczonymi przy wykorzystaniu oprogramowania FLAC dla stropu tunelu w niepodpartej części czołowej, co potwierdza wiarygodność wyników symulacji. Ponadto, wyniki symulacji wykazują znaczne zmniejszenie osiadania gruntu i niestabilności tunelu w części czołowej tunelu wzmocnionej przez podbijanie gruntu.

Słowa kluczowe: modelowanie numeryczne, gwoździowanie gruntu, drążenie tuneli przy pomocy tarcz, szkody górnicze lub osiadanie gruntu

1. Introduction

Tunnel construction in metropolitan cities is increasing worldwide due to space limitations and environmental concerns especially for shallow depth tunnels. The main objectives in the tunnel excavation are evaluation and control of ground settlements, deformations, stability of the excavation front and finally stresses developed in the lining (Galli et al., 2004).

It is very usual that excavation process is halted and a distance of excavation remains unsupported which can cause instability and ultimately surface subsidence in the tunnel (Karakus, 2007). It is a well known fact that unsupported span length is an important parameter in tunnel stability and influences the soil deformation intensity and rapidness within the unsupported span before the lining is installed (Oettl et al., 1998).

In circumstances prone to instability, application of stabilizing methods such as core reinforcement (soil nails) is necessary to control deformations in the tunnel face (Ng & Lee 2002). Previous utilization of the soil nails in stabilising tunnel faces has been studied by many researchers revealing that application of soil nails in the tunnel face can effectively improve face stability and reduce destructive deformations of overburden ground. Lundardi et al. (1992) reported field monitoring of the excavation projects in both rocks and soils have indicated that the reinforcing systems are very effective in the excavation stability maintaining a satisfactory advance rate. Lunardi et al. (2008) showed that in poor geotechnical conditions such as soft saturated soil, fibre glass soil nails can effectively stabilise the tunnel face. Grasso et al. (1989) described competent utilization of the soil nailing method in an Italian high speed railway project, which resulted in reducing tunnel wall instability during the excavation period.

Numerical analysis is a powerful tool for studying the reinforcing effects of a nailing system in tunnel excavation. Galli et al. (2004) conducted a series of three-dimensional numerical modelling to study the stabilising effects of core reinforcement by soil nails. Also, Peila (1994) conducted a series of three-dimensional finite element analyses to study the stabilising effects of the core reinforcement by soil nails. During the investigation, he concluded that tunnel face deformations and stress variations in the core ahead of the excavated tunnel can significantly be reduced by soil nailing whereas wall radial deformations and plastic zones around the tunnel perimeter can be controlled by installed lining. Several applications of 3D numerical modelling for the tunnel projects have been reported in the literature (Gioda & Swoboda, 1994; Negro & de Queiroz, 2000; Dias & Kastner, 2000; Prusek & Bock, 2008).

The effectiveness of the soil nailing is influenced by several factors such as nailing pattern and grouting efficiency from one side and nail characteristics including length, diameter and (strength) stiffness from other side (Mair & Taylor, 1997). In this paper, the effect of the face nailing on stability of the Tehran metro tunnel line # 4 was investigated studied using finite difference software FLAC 3D (FLAC 2005). This site experienced surface subsidence in a long operational gap due to machine (shield) break down and development of unsupported span.

2. Case Study

The line 4 of Tehran metro is a very long tunnel that is excavated in the west- east direction. For the present investigation, Q4-R4 section of this metro line in which surface subsidence was executed during the extraction process was considered to simulate in this study. The tunnel geometry is circular with a diameter of around 9 m and cover depth of 9 m (Fig. 1).

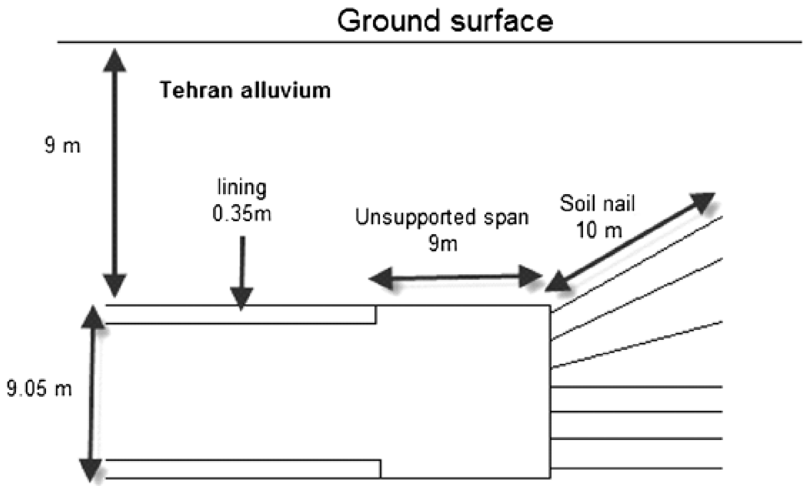

Fig. 1. Tunnel geometry and ground condition

The tunnel was excavated using shield tunnelling method. Length of the shield was 9 m and therefore, special care should have been taken for nonstop operation to prevent any possible ground subsidence and machine trap due to poor geotechnical properties of rocks. In the excavation process of the Tehran metro tunnel line 4, there was 2 months gap in the operation due to shield damage, which resulted in ground settlement and other ground disturbances.

3. Numerical modelling

As a matter of fact, tunnel stability is influenced by the face zone and 2D modelling may not be adequate under this condition. As it is evident from figure 3, passing through undisturbed (unexcavated) zone to stabilised (supported) zone, the state of stress is converted from triaxial to biaxial which indicates the necessity of 3D modelling for better understanding of deformations and stress concentrations pattern. The face zone shown in Fig. 3 is very crucial for tunnel designers because in this zone, ground condition is significantly disturbed especially in soft soils. As a rule of thumb, radius of the face zone (R_f) can be considered 1.5 times of the tunnel diameter (Lunardi, 2008).

FLAC (FLAC 2005) is one of the most popular, robust and powerful tool for modelling soil and rock behaviour in the civil and mining projects. In order to minimise the required com-

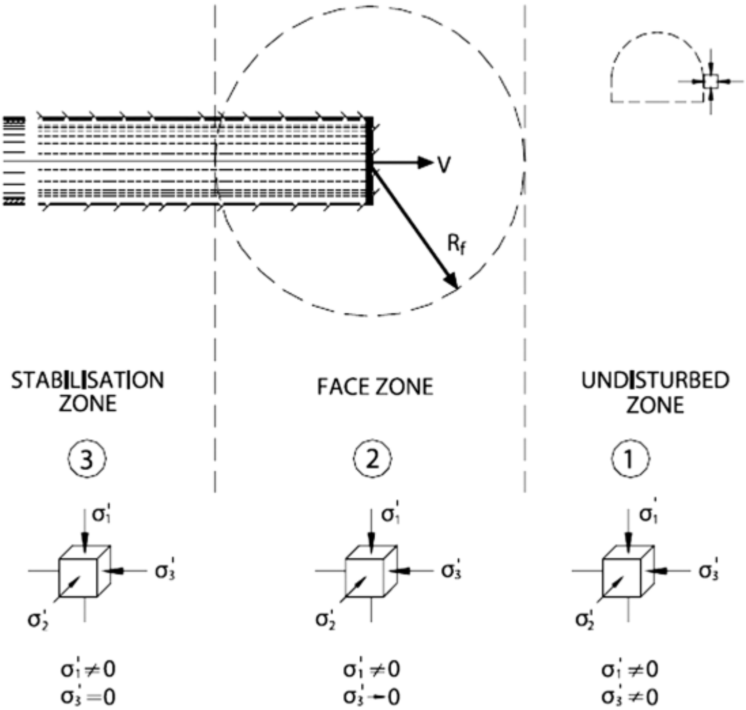

Fig. 2 Conversion of triaxial state of stress to biaxial (Lunardi, 2008)

putational time, it is always better to reduce the model size and therefore reduce the number of computational elements. Since, a symmetrical plane can be easily identified at the centreline of the tunnel, only half of the problem geometry was considered to be modelled. Fig. 3 shows mesh geometry adopted for numerical analysis. The mesh consists of approximately 81840 elements and 4000 nodes. It should be kept in mind that the greatest accuracy is obtained for a model with equal size square zones (FLAC 2005). To determine ground surface and tunnel deformations, 13 monitoring points were identified in the model. The points 1-5 are related to the vertical ground surface displacements whereas the points 6-13 are associated to the tunnel displacements and the points 6-9 will provide vertical displacements of the tunnel crown, the points 10-13 indicate changing in face horizontal deformational characterization.

Four-node shell and two-node beam elements were selected to model the segmental concrete lining and soil nails, respectively. In this construction project, thickness of the segments was considered to be 0.35 m. It was planned in such a way that the displacement in the lining and slippage between the segments and the perimeter soil wall were allowed during the analyses. A non-associated elastic-perfectly plastic Mohr-Coulomb constitutive law was considered for the materials (Vermeer & De Borst, 1984). The required input parameters that need to be specified include soil modulus of elasticity, Poisson's ratio, friction angle, dilation angle, cohesion and tensile strength. The ground geotechnical characteristics are given in Table 1. Based on in situ direct test, dilation angle was kept zero while modelling.

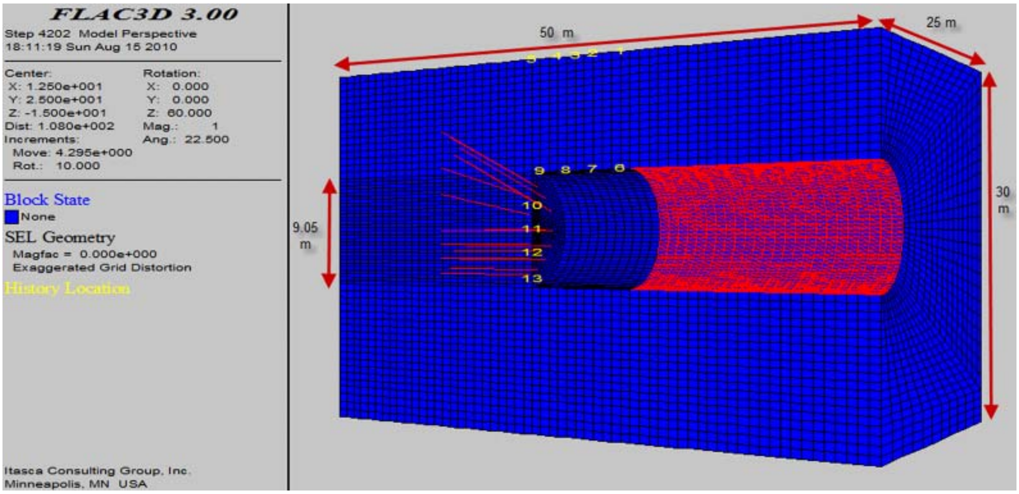

Fig. 3. Three dimensional finite difference mesh

TABLE 1

Soil parameters used in the finite difference analyses

Soil type	Height (M)	E (MPa)	Poisson's ratio	Cohesion (KPa)	Angle of friction (°)	Saturation (%)	Density (kg/m^3)
1	10	40.50	0.3	32	30	0.14	1790
2	10	41.29	0.31	31	31	0.16	1800
3	10	43.13	0.33	29	32	0.18	1900

4. Results and Discussion

Simulation of the model geometry in FLAC environment was fulfilled to evaluate the excavation effects on the ground displacements and stresses. The dimensions of the model were kept large enough to eliminate boundary effects on the modelling results. The ground and the respective soil-weight were modelled by initializing gravitational stresses to the model elements and let the model reach in equilibrium state. The Mohr-Coulomb constitutive behavioural law was applied for the material. Tunnel excavation was performed after preparation of the initial state of the model, the structural elements were considered to simulate lining support behind the shield. In this stage, the software was set to run to investigate the effects of passing time on the displacements and stress concentrations. The results of this run are demonstrated in the figures 4-6. As it is evident from Fig. 4, vertical displacements computed by the FLAC software in the tunnel crown (monitoring points 6-9) are almost identical to that of the field measured displacements. It should be mentioned that a difference of 11-16% was observed numerically between predicted values and actual recorded ones that shows the strength and validity of numerical simulation. It can also be observed that maximum displacement is recorded at point 8, at a distance of 3 m from the tunnel face. Moreover, predicted vertical displacements of the ground surface (the points 1-5) are shown in the Fig. 5. The maximum vertical displacement recorded is about 41 mm (point 4) which occurred more or less above the monitoring point 8. In the urban areas, this much of ground settlement can cause serious damages to the surface structures and create havoc in public posing threat and loss to economy and lives. Furthermore, displacements of the tunnel face are depicted in Fig. 6. As it is clearly seen in the figure, the horizontal face displace-

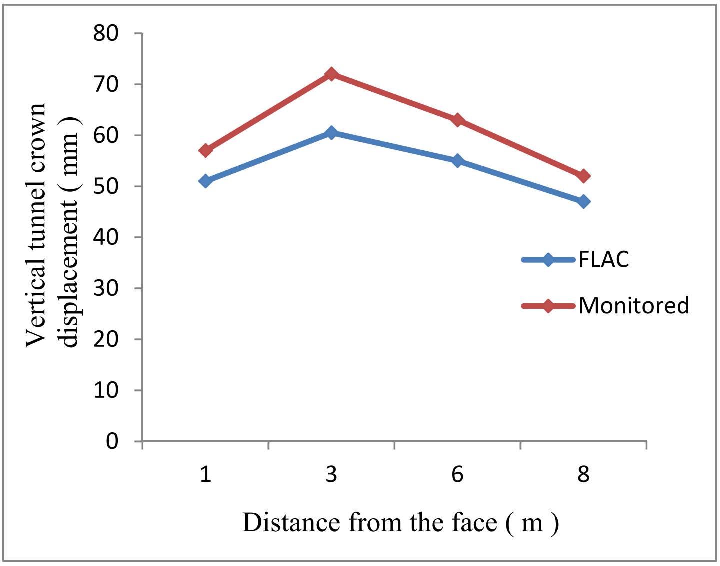

Fig. 4. Vertical tunnel crown displacement

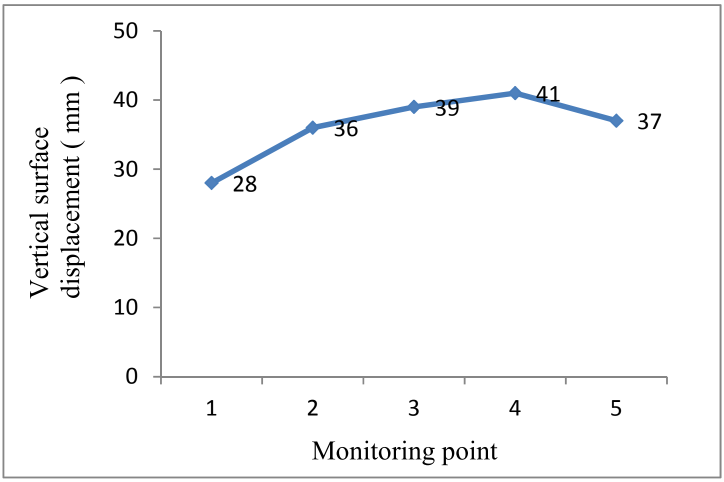

Fig. 5. Vertical surface displacement

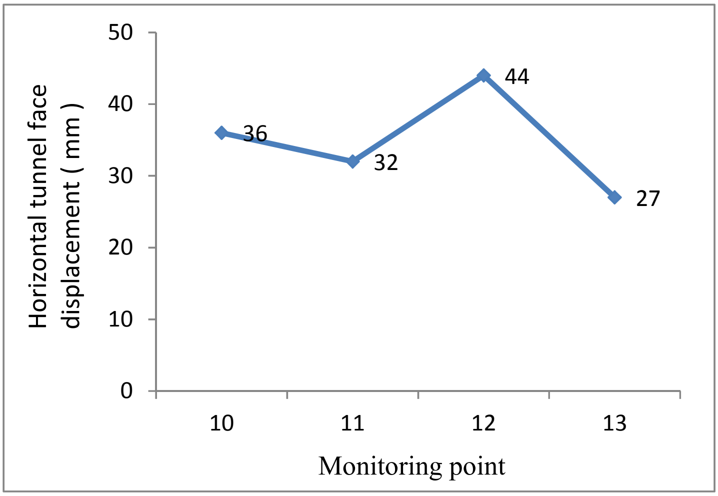

Fig. 6. Horizontal tunnel face displacement

ments are mainly against advancement direction toward the excavated part of the tunnel. The maximum horizontal displacement of the tunnel face is observed at point 12 located in lower part of the tunnel. As a matter of fact, these displacements are used to identify initiation of instability especially in loose rock and soil (Lunardi, 2008).

As a solution to stabilize excavated tunnel during the event of process halting, the approach "*control ahead of the face*" can be employed (Lunardi, 2008). By considering this approach, various methods such as grouting, fore-poling and nailing can be utilized to improve face strength, but from implementation and excavation adverse effect point of view, nailing method can be considered as the most preferred alternative (Lunardi, 2008; Pottler, 1992; Pelli et al., 1986; Geisler, 1985). In this regard, fiber glass nailing as the most practical method in use, can satisfy all the above mentioned requirements for an appropriate nailing. Ng and Lee (2002) pointed out that magnitude of tunnel face displacement is governed by many factors such as nail strength, tunnel size and state of stress. They also exclusively concluded that Young's modulus of the soil nails have considerable effect on decreasing face displacement. Moreover, Hallak et al. (1999), Calvello and Taylor (1999) used centrifuge physical modelling, to investigate the effectiveness of the tunnel face nailing. In this paper, nailing method was adopted for improving face rigidity of the Tehran metro tunnel line # 4.

Length of plastic zone ahead of the face and around the tunnel was determined. As it can be seen from Fig. 7, a large number of plastic zones are observed above the tunnel crown that can be attributed to weakness on the tunnel face. In the next step, according to the plastic zone, a soil nail pattern was selected and employed for stabilizing the tunnel face (Fig. 8). It should be mentioned that horizontal nails were applied in the lower part of the face whereas in the upper part and extending above crown level, upward inclined nails were inserted (Lunardi, 2008). Details of the nailing design are given in the Table 2. And nailing pattern is evident in Fig. 8.

Figures 9-11 demonstrate ground surface, tunnel crown and tunnel face displacements, respectively. As it is clear from Fig. 9, maximum displacement in the ground surface is around

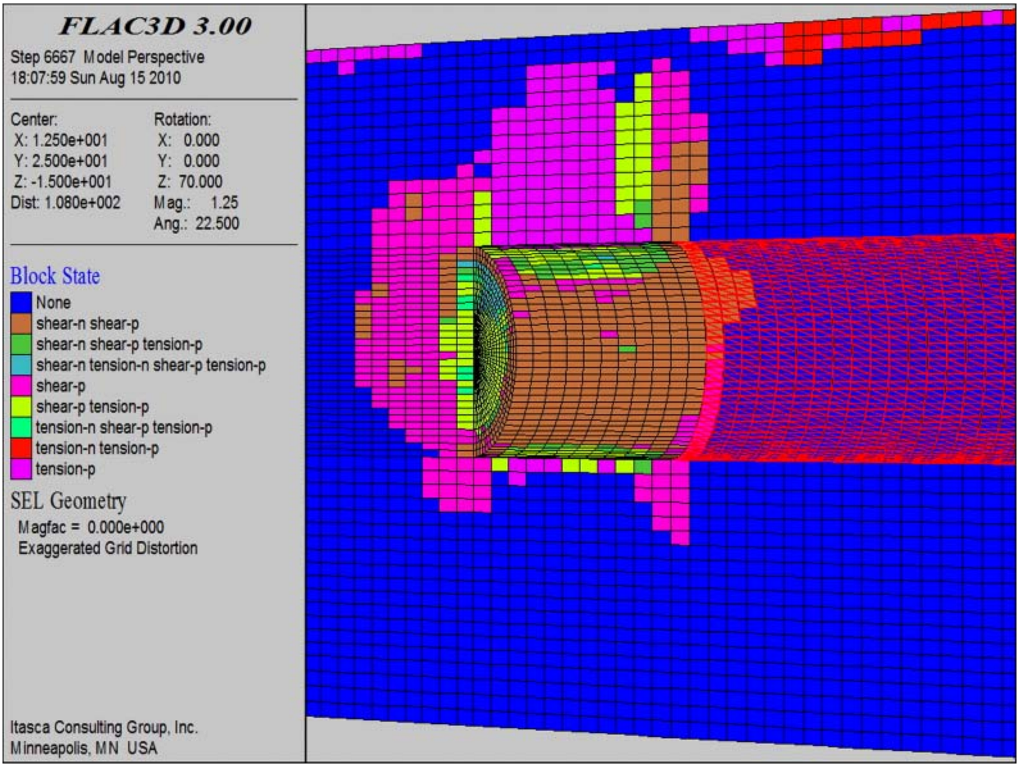

Fig. 7. Plastic zone around the cavity

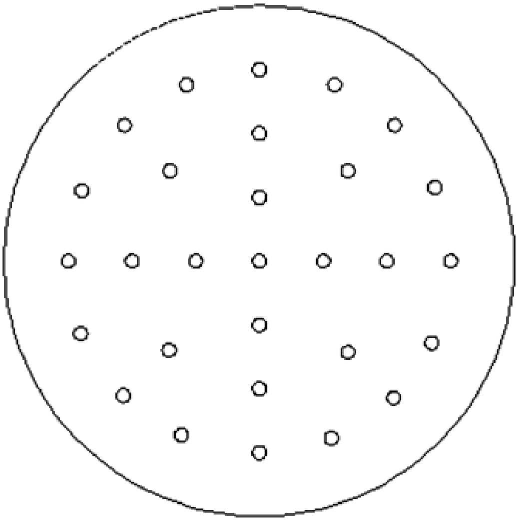

Fig. 8 Applied nailing pattern

TABLE 2

Details of the nailing design

Number	Diameter (m)	Length (m)	Poisson's ratio	Yield stress (MPa)	Young's modulus of soil nails (GPa)
29	0.12	10	0.3	30	15

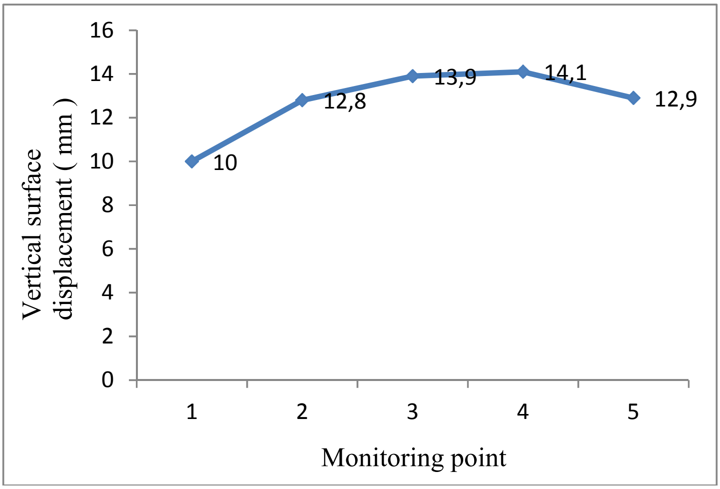

Fig. 9. Vertical ground surface displacement after tunnel face nailing

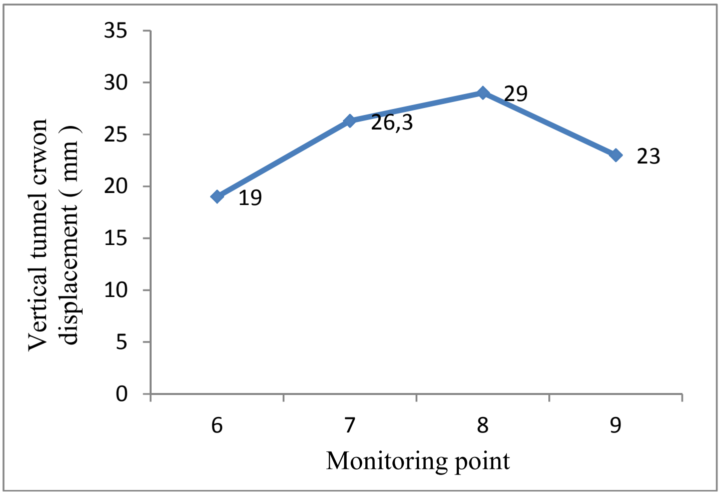

Fig. 10. Vertical tunnel crown displacement after tunnel face nailing

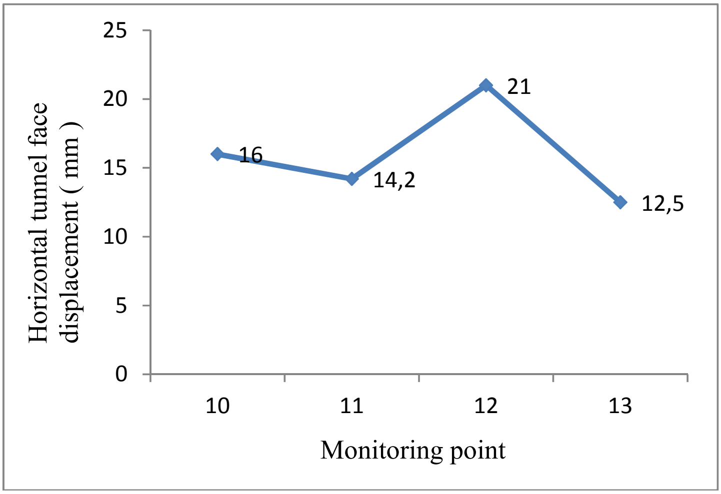

Fig. 11. Horizontal tunnel face displacement after tunnel face nailing

14.1 mm. Moreover, Fig. 10 shows considerable decrease in displacement of around 30 mm on the tunnel crown. Furthermore, as compared to unsupported face, significant diminishing of almost 50% can also observe in the tunnel face displacement.

5. Conclusions

Numerical modelling was employed for simulating effectiveness of soil nailing for increasing tunnel face strength to prevent ground subsidence and tunnel instability due to a long halt in excavation process of the Tehran metro project. Finite difference software FLAC suitable for homogenous mediums was used to simulate various conditions, i.e., unsupported and supported tunnel face. In the unsupported case, measured tunnel instability and ground subsidence were almost identical to that of the predicted values by numerical modelling and just a difference of 11-16% was observed. Also, in case of supported face, it was observed that soil nailing is very effective in increasing face strength properties and reducing ground subsidence and tunnel instability for better tunnelling and stability.

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