IJMGE
Int. J. Min. & Geo-Eng.
Vol.49, No.2, December 2015, pp.297-307.

On the selection of an appropriate excavation pattern for urban tunnels with big cross-section: A case study

Roohallah Bolghonabai[1], Mohammad Farouq Hossaini[2], Mohammad Mohammadi[1*] and Ali Nazem[3]

1. The Alborz Tunnel site, General Mechanic Contracting Co., Alborz, Iran
2. School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran
3. PhD candidate, Colorado School of Mines, USA

Received 26 Apr. 2015; Received in revised form 30 Dec. 2015; Accepted 30 Dec. 2015
**Corresponding author Email: M.mohammadi64@alumni.ut.ac.ir, Tel.: +98 9380232946.*

Abstract
Among various practical measures used for restriction of the ground surface settlement in such tunnels driven in soft ground, selection of an appropriate excavation method plays a significant role. In this paper, employing suggested diagram by Yu & Chern, corresponding values of Niayesh tunnel has been inserted into the diagram. Later, two excavation methods namely: central diaphragm and side drift methods have been suggested and numerically modeled using Finite Difference Method. Side drift excavation pattern has finally been selected since it causes less settlement. To reach an optimized selection of excavation sequence through side drift method, seven excavation patterns have thus been recommended and numerically modeled. Results have revealed that the first pattern causes the least amount of settlement. Consequently, the aforementioned excavation pattern has finally been considered as an appropriate excavation pattern encompassing optimum excavation sequence for Niayesh tunnel.

Keyword: *Full-face cross-section, Ground surface settlement, Niayesh tunnel, Sequential excavation.*

1. Introduction

Tunnel excavation using traditional methods in urban soft grounds is found to be one of the major elements inducing settlement and displacement on ground surface and in medium around the underground opening respectively. The effect of those displacements in urban areas where broad spectrum of structures and facilities have been established on the ground surface is basically of profound importance. Accordingly, not only should the tunnel stability be taken for granted, but displacements also ought to be controlled and minimized.

Generally, tunneling in soft ground invokes huge amount of complexity and sensitivity to deal with. Similarly, tunneling in urban areas has its own consequences. Small overburden, often uncemented and soft ground, or even nearby foundations and buildings appear to be major factors making settlement, occurring in urban areas, highly important to be controlled [9,7]. One of the most important factors contributing to controlling settlement in urban areas is found to be an appropriate selection of excavation method. Given the fact that the majority of tunnels excavated in urban areas, similar to soft ground, possess big cross-section, full-face excavation is no longer applicable. Furthermore, sequential excavation is considered as an appropriate alternative to be employed in such grounds. There are indeed numerous parameters controlling excavation sequences such as tunnel geometry, ground properties around the opening, and groundwater level.

Decisions over proper and compatible excavation method are often hard to make. In recent years, attempts have been given to design for tunnels in urban area diverse excavation methods. Jethwa [6] introduced different excavation methods as function of uniaxial compressive strength, so-called UCS. Sequential excavation method, known as SEM, is defined such that tunnel face is broken down to several smaller faces, so-called drifts, in order to increase the stability of tunnel face and to lessen ground surface settlement as well. Variety of parameters such as safety, cost, and scheduling plan take control of excavation method selection and of optimized determination of excavation sequences [5].

Since tunnels in urban areas are associated with low depth, soft ground, and presence of structures and facilities on the ground surface, optimum selection of excavation pattern along with well-designed sequences of excavation-if SEM has been chosen- has the potential to control ground surface settlement. Although couple of technical and economic issues meddles in excavation pattern selection, no comprehensive approach, able to appropriately select an excavation method, has yet been introduced worldwide.

The first part of this paper is to introduce a proper excavation pattern, also compatible with the properties of Niayesh tunnel, using suggested diagram by Yu & Chern[11] and numerically modeled patterns yielded by mentioned diagram for Niayesh tunnel as well.

2. Case study: Niayesh Tunnel Project

2.1. Tunnel specifications

Niayesh road tunnel project is a mouth shaped twin tunnel (north and south tunnel) constructed in urban area between Niayesh and Sadr highways in Tehran, Iran (Fig. 1). This project is the biggest tunneling project in urban area in Middle East for its length, big cross sections and step of the route. The major characteristics of Niayesh tunnel are listed as bellow [4]:

- Heavy traffic along the highways and connecting roads above the tunnel.
- High building intensity in several areas of the tunnel alignment.
- Sewers and pipes above the tunnel route and old sewers with unknown locations.
- Military structure close to the project area.
- Highway bridges crossing the alignment of the tunnel.
- Low overburden in some area with soft ground and man-made features with high water inflow in some regions.
- Passing beneath the Mellat Park Lake.
- Many Bifurcations with large cross sections along the tunnel route.
- Limitations for instrument’s installation at the tunnel route and on the buildings and other surface structures.
- Inadequate site investigations due to a lack of permission especially in residential area.

2.2. Geology

Tehran is located in alluvium called Tehran Alluvium. This alluvium is divided into 4 formations based on geological characterizations: “A”, “B”, “C” and “D” formations. Stratigraphy of Tehran Alluviums and its attributes features were presented in Figure 2 and general characteristics different parameters of Niayesh tunnel project are presented in Table 1. According to geology map of Tehran, prepared by Geological Survey of Iran (GSI), this project is located within the “A” to “B” formations. Based on results of boreholes, test pits and trenches along the tunnels routes, the tunnels will pass through "A" and "B" formations. Thickness of "A" formation is about 1200 m so that properties of "A" formation layers are various because of varying conditions of deposition [4].

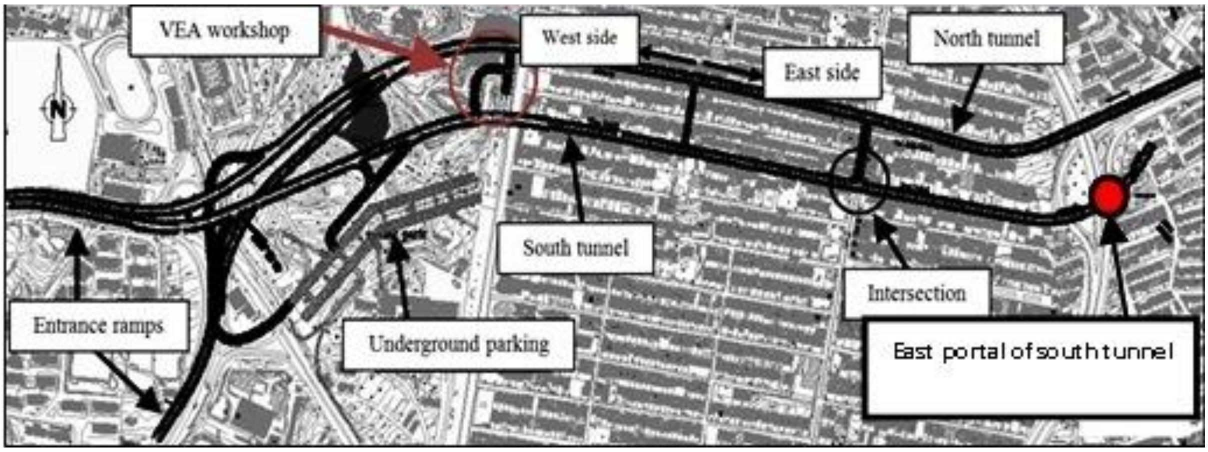


Fig. 1. plan of Niayesh tunnel project in urban area in Tehran, Iran [1]

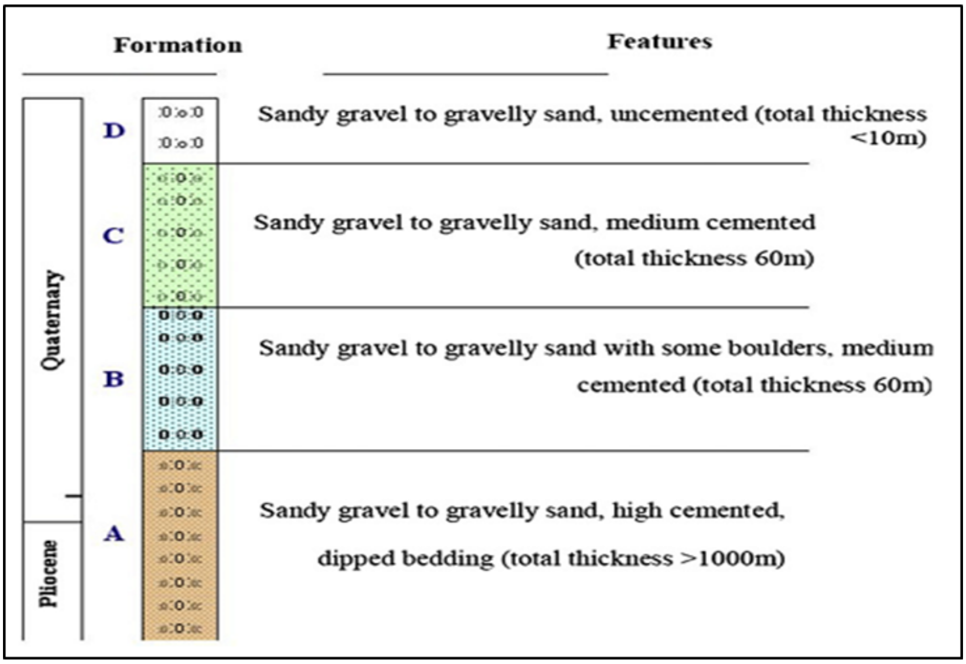


Fig. 2. Stratigraphy of Tehran Alluviums (formations) [4]

Table 1. General characteristics of Niayesh tunnel project

Niayesh road tunnel project	Main north tunnel	Main south tunnel
Length	3256m	3045m
Average Daily Traffic(AADT)	42,000	52,500
Design speed	80Km/h	80Km/h
Overburden	Max:40m - Min:4.5m	Max:38m - Min:6m
Length of access tunnel	2095m	-

3. Finite Difference Analysis

In this paper east portal of south tunnel, which was one of the critical parts of tunnel, has been selected to be analyzed (Fig. 1). Simulation of the SEM tunneling process of Niayesh 3.5 lanes cross section tunnels using Flac2D software was started with the selection of model geometry in two dimensions. Due the asymmetry of the excavation sequences, the entire domain was considered in the model. Outer boundaries are located far from tunnel so that they are not influenced by the tunnel. The selected tunnel size is approximately 13 m high and 18m wide. The model was fixed in the horizontal direction at each side and the bottom part of the boundary was pinned, so neither vertical nor horizontal movements were allowed. As can be seen in Figure 3, the top surface of the model was free in both directions.

Construction of tunnel in soft ground urban area encounter many difficulties such as face stability, ground surface settlement and tunneling-induce building damage. One of the popular methods for tunnel design and construction in urban areas is the New Austrian Tunneling Method (NATM). This is a well suited for tunneling in difficult, complex and rapidly changing geological formations.

In many countries, sequential excavation method (SEM) is currently applied to indicate soft ground tunneling without a tunnel boring machine [8]. A great variety of excavation techniques have been developed [3], which apply different methods of excavation and support. It is therefore important to investigate and compare the effect of these methods on the ground disturbance and surface settlements.

Considering the low strength of the ground and the large span of the Niayesh tunnels, a full face excavation was not possible. Therefore, the sequential excavation method was selected for this Project.

This part of the tunnel, like other part, was excavated with NATM. After excavation of each drift, lattice, with bars of radiuses 28-30 mm and shotcrete were used as a preliminary support system. Because of low overburden (about 4.5 m) in this section, lattices were installed without any spaces and thickness of shotcrete was selected to be 30 centimeter. The specification of soil used for analyses, is presented in Table 2. Table 3 shows support system characteristics.

Prior to the main analysis, numerical models were developed and verified based on measured data from Niayesh tunnel project. Figure 4 shows the verification results of the settlement trough estimated by FDM result and measured data.

Figure 4 shows good compliance between the numerical results and monitoring data. Therefore, it could be concluded that the numerical model is verified and simulations could be carried out on the developed model.

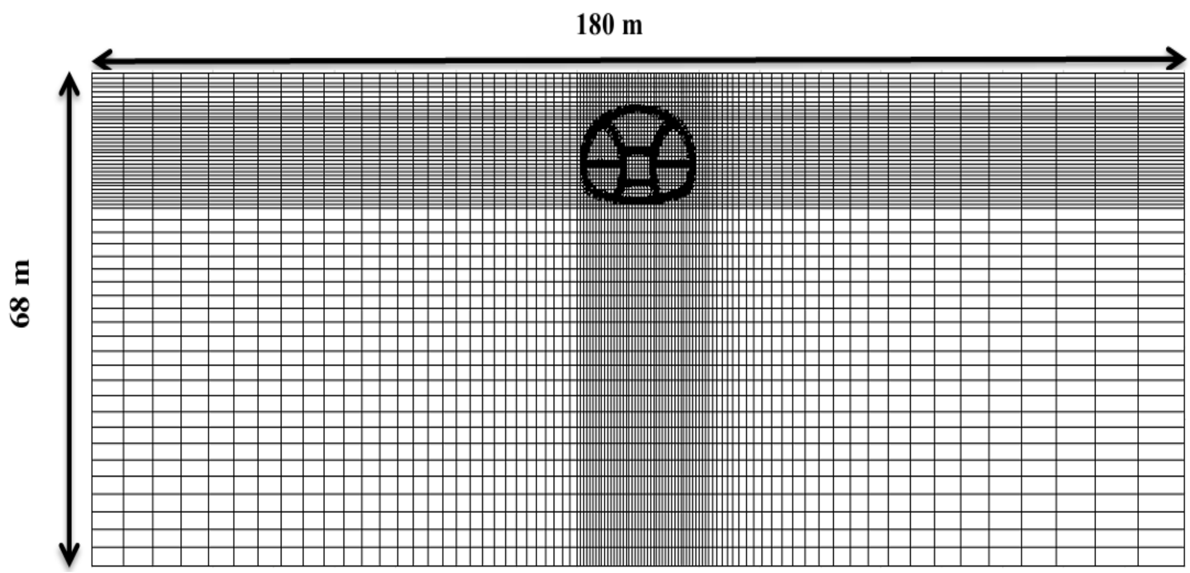


Fig. 3. Finite Difference Mesh adopted in the analysis

Table 2. The main geotechnical properties of Niayesh tunnel projects, station 2+840

Depth (m)	Density (g/cm^3)	Modulus of elasticity (MPa)	Cohesion (KPa)	Poisson ratio	Internal friction angle (Degree)	Stress ratio (K)	Overburden (m)
0-11	1.6	10	5	0.2	30	0.5	4.5
≥11	1.8	90	42	0.3	35	0.43	

Stress ratio value based on Jaky's formula for various layers of soil: ($K=1-\sin\varphi$).

Table 3. Support system characteristics

Shotcrete properties		Lattice specification	
Parameter	**Value**	**Parameter**	**Value**
Density(g/cm^3)	2	Area (m^2)	14.19 e-4
Modulus of elasticity (GPa)	20	moment of inertia of an area (m^4)	14.48 e-6
Compressive Strength (MPa)	10	moduli of elasticity(N/M^2)	4e11
Poisson's ratio	0.15	Radius of lattice's bar (mm)	28 & 32

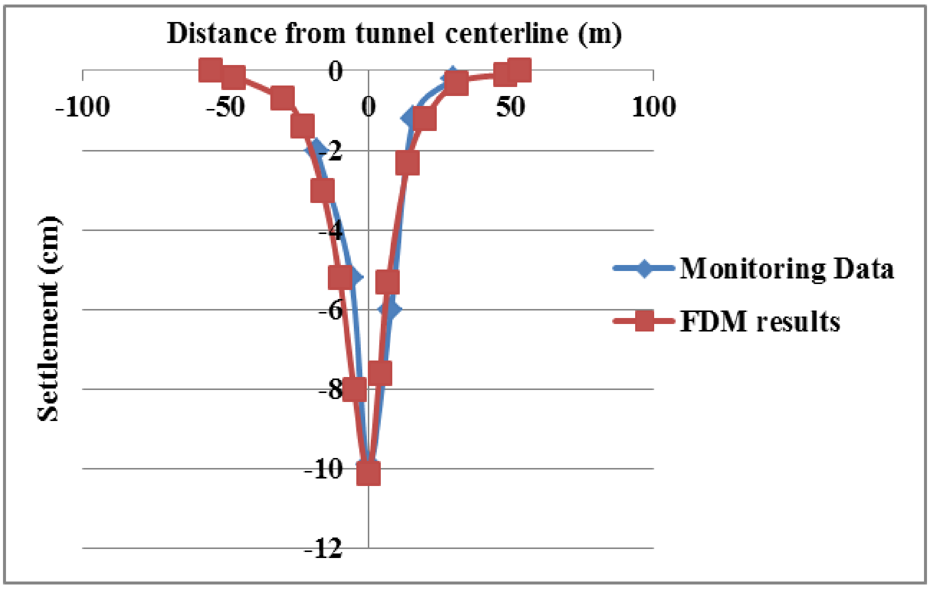


Fig. 4. Surface settlement trough obtained from analysis and Monitoring data

4. Selection of Tunnel Excavation Method

Although all efforts in recent years have focused on designing methods of urban tunnel excavation, no comprehensive approach towards selection of an appropriate excavation method has yet been introduced. It follows that engineering experiences are of more use rather than theoretical computations whenever the selection of appropriate excavation pattern comes in. Method and stages of excavation for tunnels in urban areas are chosen as a result of interaction among various elements such as safety, cost and time schedule of tunnel construction [5]. Geotechnical parameters, size and shape of tunnel cross-section, tunnel hydrogeology, in situ and induced stress status, tunnel geology and weak zones presence along the tunnel route play a significant role on the excavation method selection [11]. In the case of tunnels with large cross-sections, tunnel face is to be divided into smaller sections in order to minimize ground disturbed zone as well as ground surface settlement. In fact, dividing the tunnel face into smaller sections is an effort to maintain structural integrity of material around tunnel.

Tunnel with large cross-section is often excavated such that top heading is excavated at early stages, then the bench is taken away. Initial support is quickly installed depending on the tunnel status in terms of stability and excessive ground deformation.

In 2007 Yu and Chern [11] have suggested a graph in order for method selection of tunnel excavation in accordance with tunnel span and the ratio of uniaxial compressive strength to vertical stress shown in Figure 5. Having fitted corresponding values of Niayesh tunnel on yu and Chern graph, it was revealed that central diaphragm and side-drift excavation methods are of appropriate excavation pattern to be implemented for Niayesh tunnel. Furthermore, these two excavation patterns were nominated for appropriate selection of excavation considering ground surface settlement as well as Niayesh tunnel specifications.

Excavation stages of numerically modeled central diaphragm as well as side-drift methods have been depicted in Figure 6. Since Niayesh tunnel, according to consultant plan of project, comprises of six and seven excavation stages, for side-drift and central diaphragm consequently, excavation patterns of seven and six excavation stages have been taken into account as shown in Figure 6.

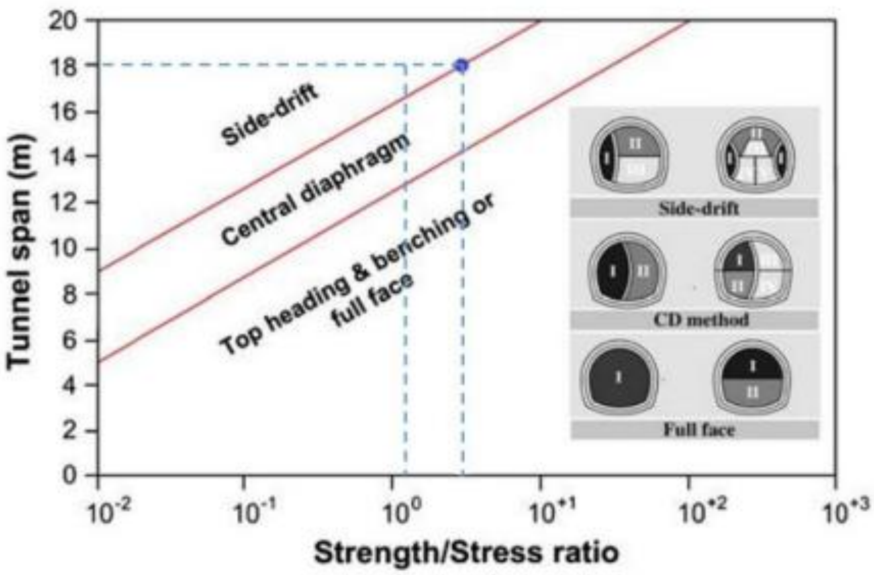
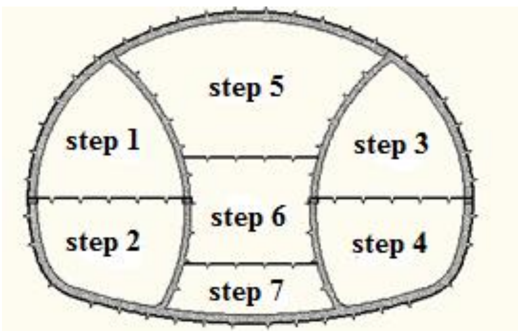
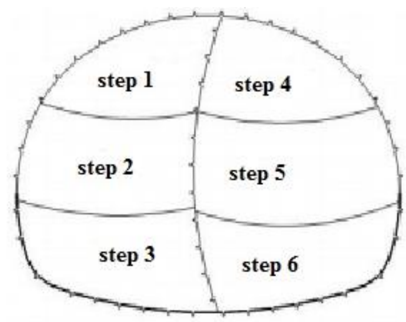


Fig. 5. Empirical determination of excavation method based on span size and the ration of uniaxial compressive strength (UCS) to vertical stress on the tunnel [11]



(a)



(**b**) Central Diaphragm (CD) method

Fig. 6. excavation stages for two excavation patterns, (a) Side Drift (b) Central Diaphragm

Modeling results of both excavation methods showed that the settlement for side drift and central diaphragm methods are 10.1 cm and 11.2 cm, respectively. Considering side drift method, settlement is zero with 55 m in distance from tunnel centerline while for central diaphragm method aforesaid distance is 60 m. According to modeling results, it is known that side drift method induces less settlement compared to central diaphragm method. Therefore, side drift has been selected as the appropriate excavation pattern and, consequently, it is to be the basis for identification of optimum excavation stages. Cross section of settlement profiles for either method are shown in Figure 7.

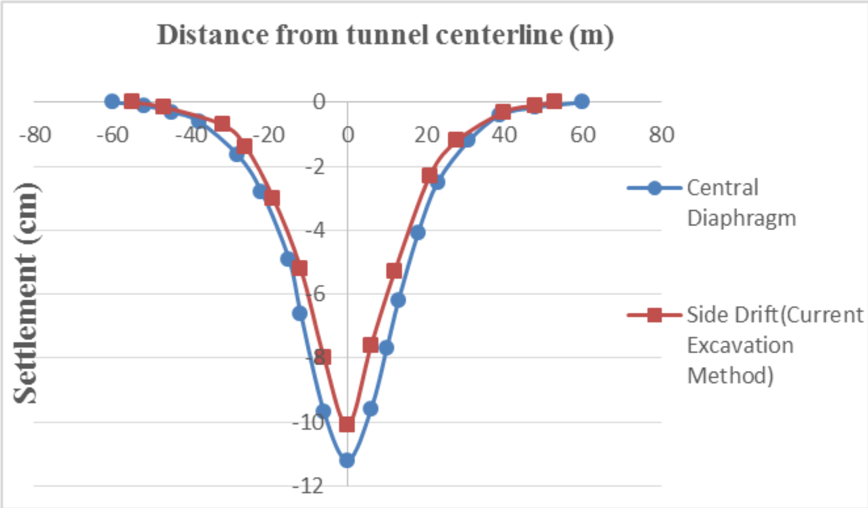


Fig. 7. Cross sectional profile of numerical modeling for side drift and central diaphragm method

5. Determination of Optimum Excavation Stages

Ground surface settlement is found to be the main parameter in optimum determination of excavation stages. Identification of excavation stages is highly dependent on many factors such as tunnel geometry, ground properties surrounding the tunnel and underground water table. Few researches have focused on the influence of implementing diverse excavation methods in tunneling performance [2]. Later studies have provided reliable information but their results are restricted to specific cases in tunneling.

Given the fact that in most cases urban tunnels are excavated with big cross sectional area, tunnel face shall be divided into smaller sections to fortify tunnel face stability and, consequently, induce less ground surface settlement. It should be noted that, from view point of designing, dimensions of these small sections of tunnel face is to be compatible with tunneling equipment and a safe chamber to excavate and install supporting system.

As it has been extensively discussed by Szechy [10], different underground openings as well as their excavation stages, if applicable, may be categorized and ordered based on several parameters, namely, excavation method, installation of temporary or permanent support system, ground nature, and in situ stress state. Furthermore, it may be of a great applicability to simulate different tunneling stages to determine optimal excavation stages.

In the present paper, to account for excavation sequence optimization, seven excavation schemes have been proposed. Using specifications of Niayesh tunnel in 2+480 chainage, numerical modeling based on side drift method for each scheme has been introduced, as shown in Figure 8. In optimizing of excavation sequences, major factors such as completion of supporting system ring, number of excavation sequences, and the excavation of central drift have also been taken into account. In order to validate results obtained from numerical modeling, instrumentation data have been employed. Several benchmarks on the ground surface for the purpose of settlement measuring, instrumentation results of surface settlement for Niayesh tunnel in 2+840 chainage and numerical modeling results for side drift method performed in this station using Finite Difference Method (FDM) have been depicted in Figures 9, 10, and 11, respectively.

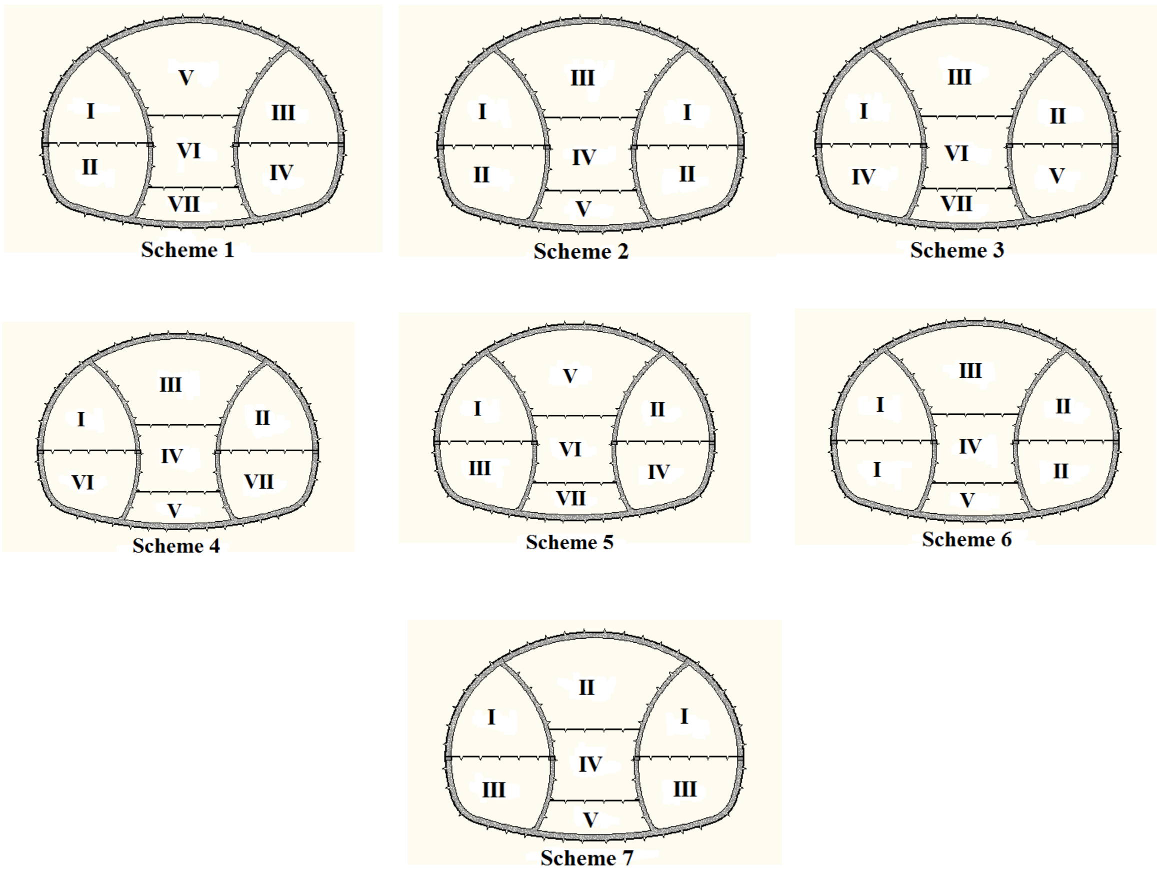


Fig. 8. Excavation schemes proposed for Niayesh tunnel based on side drift method

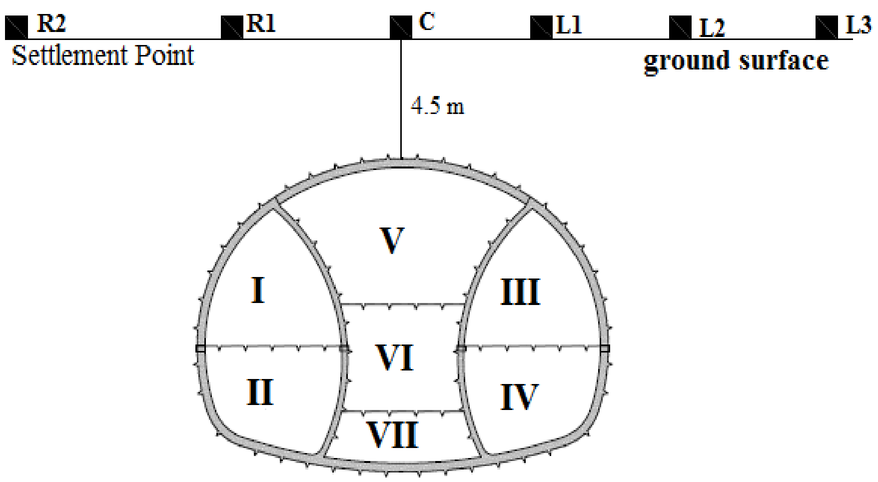


Fig. 9. A typical benchmarks on the ground surface for the purpose of settlement measurement

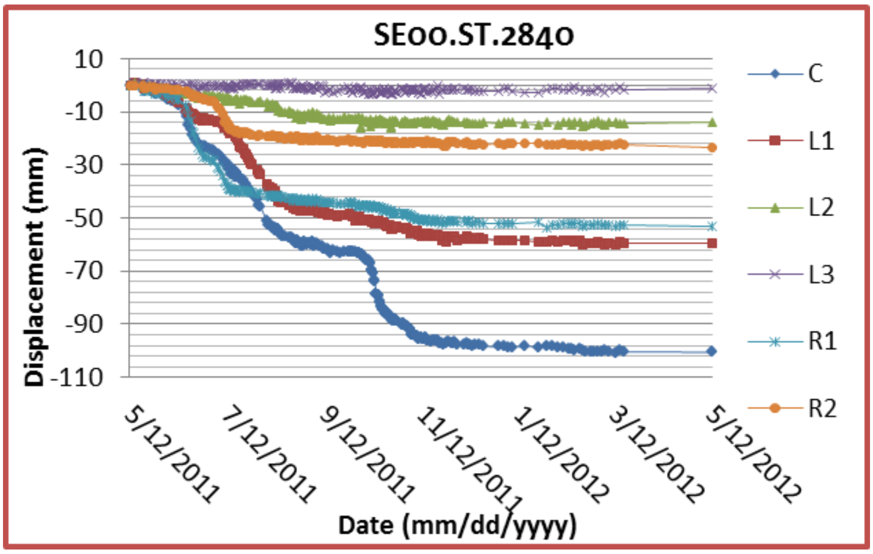


Fig. 10. Instrumentation results of surface settlement for Niayesh tunnel in 2+840 chainage

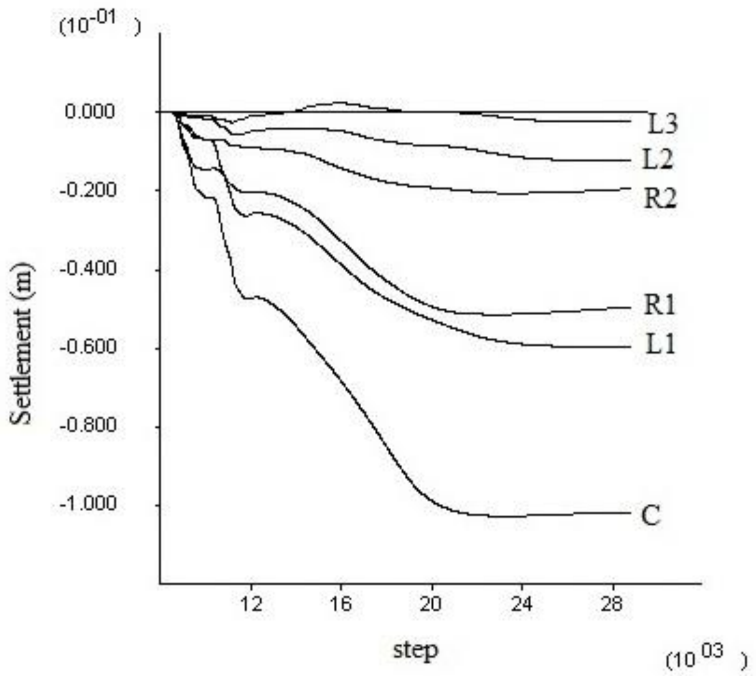


Fig. 11. Numerical modeling results for side drift method performed in 2+840 chainage

Having modeled seven proposed schemes, settlement magnitude for each scheme has been determined as their cross sectional profile shown in Figure 12. According to the results, first scheme, induced settlement of 10 cm, possessed the lowest value of settlement whereas seventh scheme had the highest settlement value of 16.8 cm. settlement value of 10 cm is found to be rational since this section of the tunnel has been covered with low strength soil as overburden and, on the other hand, is also exposed to dynamic loads induced by vehicle traffic. Therefore, first scheme has been presumed as the proper excavation scheme with optimal excavation sequences for Niayesh tunnel.

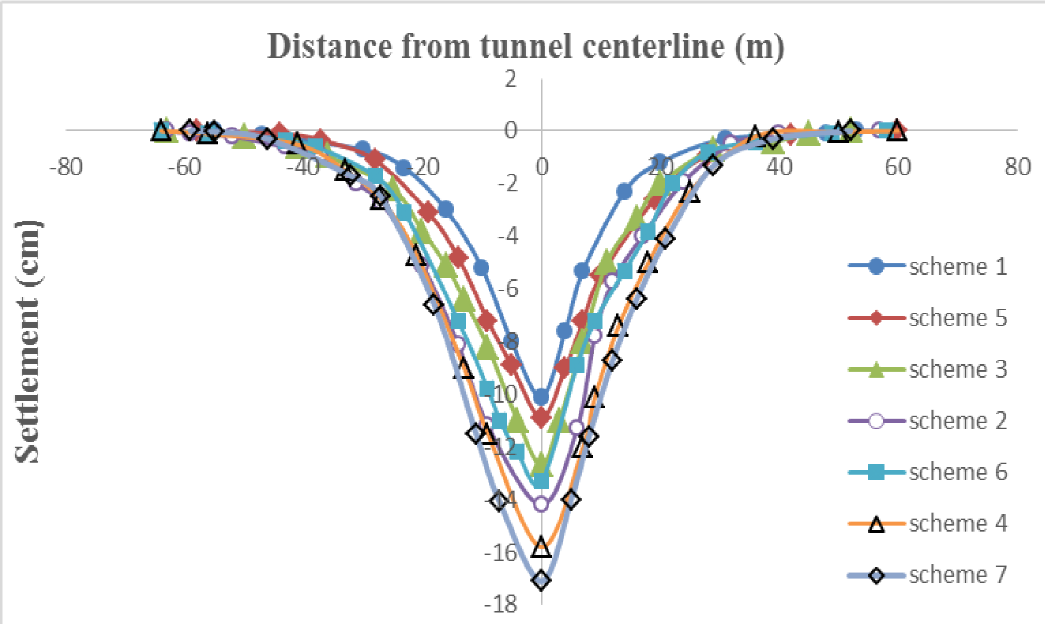


Fig. 12. Cross sectional settlement profiles for the proposed excavation schemes (in Fig. 10) for the Niayesh tunnel in 2+840 chainage

Having compared proposed first pattern with fifth pattern, both patterns consist of seven sequences of excavation. Besides, excavation of central galleries was executed after lateral galleries had been excavated. It should be noted that since the time required for support ring in the first pattern to close is less than of fifth pattern, it is basically anticipated that settlement value for first pattern would be lower than of fifth pattern. As results showed corresponding settlement for first and fifth pattern is 10 cm and 10.7 cm, respectively. Hence, the shorter the time needed for support ring to close, the less ground surface settlement shall be. This is so for either of second and sixth patterns. Since support system ring is closed sooner, settlement, consequently, is smaller as shown in Figure 12.

In the second proposed pattern, central galleries excavation takes precedence over side galleries whilst in seventh pattern is vice versa causing more ground surface settlement as shown in Figure 11. It follows that the excavation of central galleries at the end of excavation process would profoundly decrease the ground surface settlement.

Excavation volume for each stage has a reciprocal effect on ground surface settlement. Low volume of excavation shall hold for decrease in ground surface settlement while cause increase in excavation stages and, on the other hand, delay support system ring to close, which make ground surface settlement increase. Support system ring should be immediately closed with fewest numbers of stages in loose ground.

Having compared the results of numerical modeling for both sixth and seventh patterns, it can be inferred that immediate closure of support system ring and, on the other hand, central galleries excavation stage are of significant importance to control ground surface settlement. Accordingly, if the ring of support system is immediately closed along with the excavating of central galleries at final stages, settlement would considerably decrease.

6. Conclusions

In this paper by using FDM method, numerical modeling for several excavation pattern have been carried out introducing appropriate excavation method associated with optimal stages of excavation for Niayesh tunnel. Numerical modeling results are also in good agreement with ones obtained from instrumentations. This study led to the following results:

- In order to select an appropriate excavation pattern two excavation patterns, central drift and side drift, were proposed, modeled, and finally validated with results obtained from instrumentation using recommended graph by Yu & Chern. Results demonstrated that side drift excavation pattern causes less settlement and, therefore, has been selected as the appropriate excavation pattern.

- In order to optimize excavation sequences, seven excavation scheme were proposed and numerically modeled considering side drift excavation pattern. Results revealed that first excavation scheme leads to smallest value of settlement on ground surface. Furthermore, this scheme has been selected as an appropriate excavation pattern with optimal sequences.
- The time for closure of support system, number of excavation sequences, drifts area, and central drifts stage are influential elements controlling efficiency of sequential tunneling. Among these elements, closure time of support system as well as side drift excavation stage play vital role in settlement controlling of ground surface.
- Results showed that ground surface settlement reduces when central drifts are excavated at the end.
- Based on results obtained from numerical modeling, excavation volume for each stage accounts for reciprocal effect on ground surface settlement. The smaller the excavation volume, the less ground surface settles. However, low volume in excavation will increase the stages of excavation and induce delay on support system ring to close leading to increase in ground surface settlement. It is of vital importance that support system ring immediately closes in least number of excavation stages.
- Results substantiated that the less time elapses for support system ring to close along with high excavation volume and fewer excavation stages, the more potential to control ground surface settlement compared to decrease in excavation volume with increase in excavation sequences. Thus, attempt will be made to lessen excavation sequences where empirical and numerical method has the capability to optimize it.

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