# Settlement Prediction for Tehran Subway Line-3 via FLAC3D and ANFIS

S. A. Naeini, A. Khalili

*Abstract*—Nowadays, tunnels with different applications are developed, and most of them are related to subway tunnels. The excavation of shallow tunnels that pass under municipal utilities is very important, and the surface settlement control is an important factor in the design. The study sought to analyze the settlement and also to find an appropriate model in order to predict the behavior of the tunnel in Tehran subway line-3. The displacement in these sections is also determined by using numerical analyses and numerical modeling. In addition, the Adaptive Neuro-Fuzzy Inference System (ANFIS) method is utilized by Hybrid training algorithm. The database pertinent to the optimum network was obtained from 46 subway tunnels in Iran and Turkey which have been constructed by the new Austrian tunneling method (NATM) with similar parameters based on type of their soil. The surface settlement was measured, and the acquired results were compared to the predicted values. The results disclosed that computing intelligence is a good substitute for numerical modeling.

*Keywords*—Settlement, subway line, FLAC3D, ANFIS method.

## I. INTRODUCTION

TUNNEL construction in urban areas is not as easy as it is in non-residential areas. Most of the tunnels built along railways, roads, and particularly subways are constructed in shallow depths of soft grounds found within urban areas (subsurface structures' foundations or beside important urban facilities). Deformations (specially the settlement) are a common phenomenon in the course of tunneling process [5]. On the other hand, in most of such projects, it is not possible to make a change in the tunnel's path to reach reliable ground. Therefore, it is necessary to protect underground structures and facilities against possible damages resulted from tunneling process. Consequently, the tunnel should be constructed in such a way to induce minimum deformation on the ground surface, so as to minimize the damages experienced by surface structures. The mentioned points reveal the importance of proper analysis, support, compatibility of construction method and instrumentation [6]. In order to be able to control the settlement, one should be able to predict it, based on which one may consider required preventions and protections. Settlement prevention and control methods are completely dependent on the settlement prediction method, further indicating the importance of settlement prediction. Accordingly, a tunnel engineer needs to be able to make reliable prediction of ground deformations induced by tunneling [13]. To overcome these limitations, intelligent methods can be used to develop a more accurate and reliable predictive method. In the recent decade, intelligent approaches have found a special position within the efforts toward estimating the settlement as well as other tunnel deformations. Various researchers have used such methods as artificial neural network (ANN), fuzzy logic (FL), support vector machine (SVM), gene expression programming (GEP) to present models to predict settlement and other tunnel deformations; the results indicate high relative accuracy of these methods [2], [8]-[14]. Among few studies already dealt with settlement prediction using ANFIS method, one may refer to the works by Hou et al. [16] and Ahangari et al. [13]. Hou et al. [16] used such dependent parameters as surface settlement (at five points) behind the tunnel face and one operational parameter (working cycles per day) to predict surface settlement 5 m ahead of the shield face. As such, no geometric, strength, or alike factors were considered in their investigations. Rapid progress in the development of computer codes and the limitations of analytical methods and experimental methods has led to an increase in the use of numerical methods for the design and analyses of tunnel lining. A summary of analyses of tunnels up to year 2000 by Negro and Queiroz [22] and Farias et al. [23] using finite element was presented. After a study of more than 65 recently published papers, they showed that about 96% of articles are published by the Finite Element Method (FEM), while only 4% used the Finite Differences Method (FDM) or others, which shows that FEM is the most popular approach. They also noted that 92% of the published analyses are still in 2D, under conditions of plane strain hypothesis. Also, most analyses are still simple, and elastic-perfectly plastic condition is mainly used. Khalili et al. applied ANN, ANFIS, and FLAC3D approach to the Chehel-Chay tunnel crown settlement prediction and showed that ANFIS is the most accurate method [1]. ANFIS method and FLAC3D are selected to be used to predict surface settlement in this research.

## II. TEHRAN NO. 3 SUBWAY LINE AND ITS REGIONAL CHARACTERISTICS

Tehran No. 3 subway line was opened in 2014. It consists of five phases, 23 underground stations, and seven on-surface stations with a total of 35 km in length. The section of the subway line which is studied in this research is excavated with a horse-shoe profile of 6.7 m in diameter with a maximum 11.6 m of overburden using the NATM, as shown in Fig. 1.

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The tunnel has been excavated manually with an advancement of 1 m per day. With the start of a new face, the support system has been installed with 25 cm armored shotcrete. The geotechnical properties and grain size distribution of this section are presented in Table I. The elasticity modulus has been determined as 30.7 MPa by the pressure meter method (Manard) at 20 m depth and a pressure of 15 bars. Therefore, taking the tunnel depth at 11.7 m subjected to 8–9 bars, the elasticity modulus ($E_s$) can be estimated to be 17.65 MPa. The geometrical and geotechnical properties of the soil mass around the tunnel are shown in Table II [2].
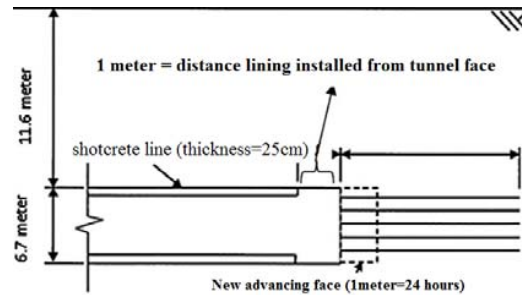


Fig. 1 Tunnel geometry and boring situation [2]

TABLE I
GEOTECHNICAL PARAMETERS AT BOREHOLE NO.5 AT DIFFERENT DEPTHS [2]

| Type of soil | | Method | Depth | LL | PI | Cc | $D_{100}$ | $D_{60}$ | $D_{30}$ | $D_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Sand (%) | Clay and silt (%) | | | | | | | | | |
| 24.7 | 64.3 | SPT1 | 1-1.45 | 26 | 8 | 1> | 6.73 | 0.0631 | 0.0116 | 0.0077 |
| 0.3 | 99.7 | SPT2 | 6.5-9.95 | 26 | 10 | 1> | 0.42 | 0.0276 | 0.0079 | 0.006 |
| 3.8 | 95 | SPT5 | 11-11.41 | 31 | 13 | 1> | 6.73 | 0.0302 | 0.0087 | 0.0074 |
| 9.7 | 88.6 | SPT6 | 14-14.95 | 30 | 12 | 1> | 6.73 | 0.0239 | 0.0084 | 0.0074 |

TABLE II
GEOMETRY AND GEOTECHNICAL PROPERTIES OF THE SOIL MASS AROUND THE TUNNEL [2]

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Young's modulus (Soil) (MPa) | E=17.65 | Step of excavation (m) | X=1 |
| Poisson's ratio | $\upsilon$ =0.36 | Tunnel depth (m) | Z=11.6 |
| Cohesion (kPa) | C=21.5 | Young's modulus (Shotcrete) (MPa) | EC=207.0 |
| Friction angle (deg) | $\varphi$ =37.5 | Support hardness (MPa) | Kc=1956.02 |
| Density (km/m3) | $\gamma$ =1700 | Shotcrete thickness (m) | TC=0.25 |
| Tunnel diameter (m) | D=6.07 | Unixial compressive strength (MPa) | $\eta$ = 55 |

## III. NUMERICAL MODELING

FLAC3D is numerical modeling software based on finite difference method. The numerical model contains a horseshoe shape cross section with height of 5.76 m, width of 6.05 m, and length of 20 m. As the tunnel is symmetric, half of tunnel model was constructed in order to decrease the volume of the model and reduce the calculation time. The impact zone was considered as three times the tunnel diameter in the model so that the induced stresses may reach to their initial amount at the distance of three times of the tunnel diameter. Therefore, the model dimensions are considered more than five times the tunnel diameter. Considering this assumption, the effect of boundary conditions would be reduced to the expected amount. Therefore, in the present study, the size of model was roughly considered to be 30 m × 45 m. Mohr–Coulomb theory is used to simulate the material behavior. Mesh dimensions are taken as much as small and dense near the tunnel that increases gradually with distance; hence, a realistic model is presented. Large strain model was carried out.

### A. Excavation Methods

NATM can be regarded as a modern school in tunneling resulted in improving tunneling activities. In the other words, an unnecessary cost in tunneling has been decreased significantly, while safety in tunneling procedure has been provided. Since there are many effective parameters in excavating and constructing an underground structure, the only way to decrease costs and provide safety is using the method which is flexible enough to make changes in design and construction. NATM is a method which has provided the mentioned flexibility in excavation, maintenance, and instrumentation [4]. NATM is adaptable to different soil conditions and different types of tunnel construction. As tunnel excavation takes place in soil conditions, the distance between the excavations levels must be short - that is performed in two or more levels, and then, the ring must be completed [3]. Application of this method in excavating tunnel in urban districts and imposing the least damage to buildings and urban infrastructure caused it to gain attention of many engineers to apply it in excavating subway tunnels.

### B. Advantages of Using NATM

1. Flexibility in presenting different patterns of tunnel geometry and excavation.
2. The need for tools and machineries with low cost.
3. Flexibility in installing extra supports such as anchors.
4. Easy installation of backup instruments and drainage.
5. Flexibility in monitoring stresses and tunnel deformations.
6. Better connection between earth and backup instruments.
7. Easy shotcrete.
8. Applicable in most of geological conditions.

This tunnel was constructed according to the principles of NATM and was divided into two main excavation stages. First, tunnel heading is excavated and support system is applied. Then, tunnel bench is excavated and support system is applied on the bench, and the process will continue in this manner. Excavation step is considered to be 1 m. After model

balance, horizontal displacement and velocity of node are set to zero, and then the tunnel is excavated [7]. Vertical displacement contours and installed support system at the end of the excavation on step 21 and step 40 in numerical simulations are presented in Fig. 2.
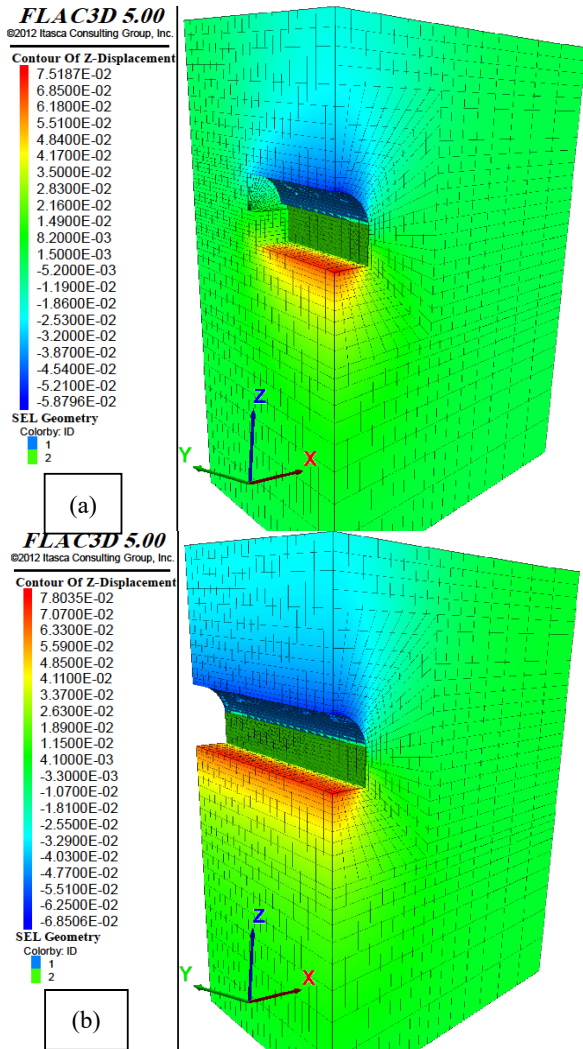


Fig. 2 Vertical displacement contour at (a) step 21 & (b) step 40

The maximum settlement is found in the tunnel centerline. It is calculated to be about 68.5 mm. The maximum displacement of the surface is detected in the tunnel center which is about 31 mm. There is a decrease in the settlement as one moves away from the tunnel centerline. The vertical displacement histories in Fig. 3, recorded at two monitoring points, indicate that the maximum surface settlement with red line and tunnel crown settlement with blue line under excavation.

As shown in Fig. 3, the surface settlement is indicated with red line and blue line is the tunnel crown settlement. Liner displacements are shown in Fig 4.
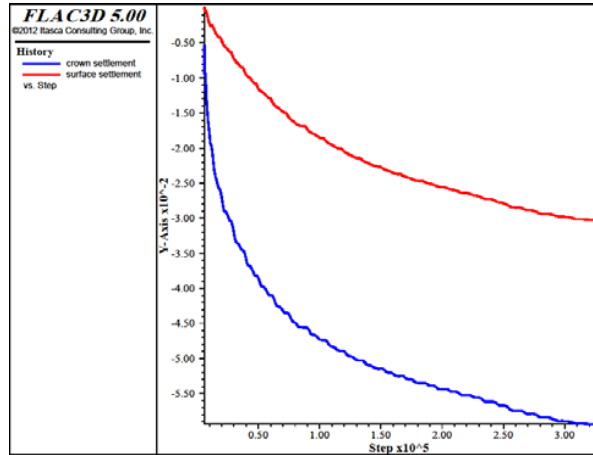


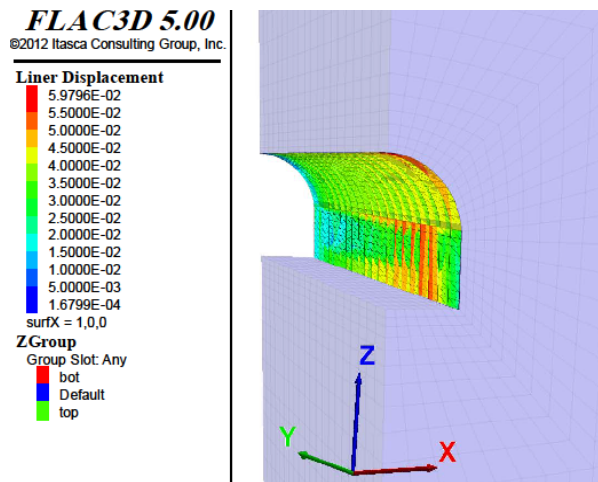Fig. 3 Vertical displacement histories for settlement crown and surface with support



Fig. 4 Liner displacement at the end of install support system

## IV. ESTIMATION OF MAXIMUM SURFACE SETTLEMENT BY ANFIS

ANFIS is created with the combination of neural network and FL [17]. Fuzzy systems and ANNs include various advantages and disadvantages. In a fuzzy system, qualitative aspects of knowledge and human reasoning process could be a model, whereas it does not feature any earning capabilities. In the other words, a fuzzy system cannot be trained. Nevertheless, neural networks are able to do self-training using datasets. However, ANNs are implicit and they are unable to use human language [18]. To overcome these deficiencies, ANFIS has been proposed. ANFIS has the advantages of both fuzzy and neural systems [19], [15].

According to Fig. 5, ANFIS process acts in five steps: Layer 1 is an input layer; Layer 2 is an input member functions layer (for fuzzification of inputs); Layer 3 is a rule layer; Layer 4 is an output member functions layer (for defuzzification of outputs); and Layer 5 is an output layer [13]. In this system, training means that, with the use of training data, the non-linear parameters related to the fuzzy

membership functions at the first level and the linear parameters of the forth layer are determined in a way that for each desired input, a favorable output is obtained. Membership function parameters are regulated through the back propagation (BP) algorithm or in combination with the least squares (LS) method in during neuro-fuzzy process [20], [21]. Therefore, this technique can be used to settlement prediction corresponding to the tunnel geometry and geomechanical properties. By applying this manner and using similar structure data, the network is trained for determining appropriate algorithm, and the maximum settlement is predicted according to field parameters.
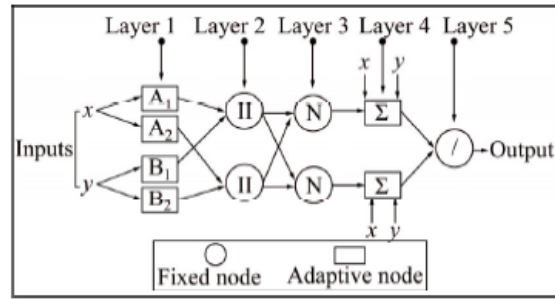


Fig. 5 ANFIS structure

TABLE III
SAMPLES USED FOR NETWORK TRAINING AND VALIDATION TESTING [2]

| Name | C (kPa) | Ø (°) | E (MPa) | Z (m) | D (m) | $S_{max}$ |
|---|---|---|---|---|---|---|
| Tehran 3 | 12 | 38.5 | 24.5 | 12 | 6.7 | 37 |
| Tehran 3 | 11 | 35 | 12.7486 | 8.6 | 6.55 | 36 |
| Tehran 3 | 30 | 35 | 20 | 12.5 | 6.05 | 32 |
| Tehran 3 | 27 | 25 | 27.7 | 16.8 | 6.7 | 27 |
| Tehran 3 | 25 | 42 | 14.71 | 15 | 8.3 | 33 |
| Tehran 3 | 14.3 | 28 | 17 | 13.7 | 6.7 | 31 |
| Tehran 3 | 8 | 33 | 9.7 | 15 | 6.7 | 37 |
| Tehran 3 | 15.69 | 40 | 8.82598 | 8.6 | 6.55 | 8.6 |
| Ahvaz | 12.22 | 28.77 | 16.77 | 12 | 9 | 36 |
| Ahvaz | 12.22 | 28.77 | 16.77 | 14 | 7 | 20 |
| Ahvaz | 12.22 | 28.77 | 16.77 | 13 | 8 | 27 |
| Ahvaz | 12.22 | 28.77 | 16.77 | 11 | 10 | 44 |
| Ahvaz | 14 | 35.4 | 28 | 9 | 9 | 32 |
| Ahvaz | 14 | 35.4 | 28 | 15 | 9 | 38 |
| Ahvaz | 14 | 35.4 | 28 | 18 | 9 | 46 |
| Ahvaz | 14 | 35.4 | 28 | 12 | 9 | 31 |
| Ahvaz | 23 | 37 | 19.7 | 12 | 9 | 27 |
| Ahvaz | 23 | 37 | 19.7 | 12 | 9 | 24 |
| Ahvaz | 23 | 37 | 19.7 | 12 | 9 | 20 |
| Istanbul metro | 80 | 25 | 58.83 | 19 | 6.5 | 80 |
| Istanbul metro | 80 | 25 | 58.83 | 19.6 | 6.5 | 230 |
| Istanbul metro | 80 | 25 | 58.83 | 42 | 6.5 | 40 |
| Istanbul metro | 80 | 25 | 29.42 | 13.1 | 6.5 | 43 |
| Istanbul metro | 80 | 25 | 29.42 | 11.2 | 6.5 | 90 |
| Istanbul metro | 80 | 25 | 49.03 | 14.8 | 6.5 | 110 |
| Istanbul metro | 80 | 25 | 49.03 | 22.5 | 6.5 | 80 |
| Istanbul metro | 80 | 25 | 49.03 | 15.25 | 6.5 | 230 |
| Tabriz | 12 | 32 | 24.5 | 20 | 6.7 | 30 |
| Tabriz | 10 | 36.1 | 24.5 | 8.41 | 6.7 | 3 |
| Tabriz | 5 | 37.1 | 24.5 | 9.04 | 6.7 | 15 |
| Tabriz | 5 | 37.1 | 24.5 | 9.36 | 6.7 | 11 |
| Tabriz | 5 | 37.1 | 24.5 | 9.68 | 6.7 | 14 |
| Tabriz | 3 | 35 | 24.5 | 10 | 6.7 | 31 |
| Tabriz | 2 | 38.5 | 24.5 | 10.32 | 6.7 | 45 |
| Tabriz | 2 | 38.5 | 24.5 | 10.63 | 6.7 | 41 |
| Tabriz | 2 | 38.5 | 24.5 | 10.95 | 6.7 | 40 |
| Tabriz | 1.8 | 32.2 | 24.5 | 11.26 | 6.7 | 42 |
| Tabriz | 3 | 35 | 24.5 | 11.55 | 6.7 | 31 |
| Tabriz | 3 | 35 | 24.5 | 11.65 | 6.7 | 31 |
| Tabriz | 10 | 36.1 | 24.5 | 11.76 | 6.7 | 12 |
| Tabriz | 10 | 36.1 | 24.5 | 11.78 | 6.7 | 8 |
| Tabriz | 3 | 35 | 24.5 | 12 | 6.7 | 35 |
| Tabriz | 4.5 | 33 | 24.5 | 10.45 | 6.7 | 19 |
| Tabriz | 2 | 38.5 | 24.5 | 10.45 | 6.7 | 41 |
| Tabriz | 2 | 38.5 | 24.5 | 10.45 | 6.7 | 39 |
| Tabriz | 1.4 | 38 | 24.5 | 11.68 | 6.7 | 41 |
| Tabriz | 1.7 | 37 | 24.5 | 11.88 | 6.7 | 44 |
| Tabriz | 5 | 37.1 | 24.5 | 12.16 | 6.7 | 15 |

ANFIS has been designed using MATLAB software. The data used for the subsidence prediction by ANFIS method are from the measured settlement in 46 subway tunnels in Iran and Turkey with similar soil properties presented in Table III using the NATM method. From the parameters used for simulating the ground behavior during excavation, five parameters are considered as effective pertinent to settlement. These parameters are given in Tables III and IV. The maximum and minimum values of these parameters are specified in Table V.

Among 46 data, 41 data were randomly selected for training network, five data for testing. This modeling approach employed sub-clustering to develop FIS. The overlap of functions was chosen to be around 35%. Various membership functions were utilized to explore the network. Ultimately, Gaussian membership function was selected due to its minor errors as compared to other functions. Training was carried out through Hybrid training algorithm in order to parameter optimization with epochs 80. The average error was estimated to be around 0.0049 in test.

TABLE IV
PARAMETERS USED IN SIMULATION

| Parameters (Symbol) Unit | Cohesion (C)(kPa) | Friction angle (Ø)(°) | Elasticity modulus (E) (MPa) | Tunnel diameter (D)(m) | Depth (Z)(m) | Settlement (S)(mm) |
|---|---|---|---|---|---|---|
| Input No. | 1 | 2 | 3 | 4 | 5 | Output |

TABLE V
MINIMUM AND MAXIMUM AMOUNTS OF INPUT PARAMETER

| Parameters (Symbol) Unit | Cohesion (C) (kPa) | Friction angle (Ø) (°) | Elasticity modulus (E) (MPa) | Tunnel diameter (D) (m) | Depth (Z) (m) |
|---|---|---|---|---|---|
| Value | 1.4-80 | 20-38.5 | 3-58.83 | 2.47-10 | 8.41-42 |

Fig. 6 is an overview of rules about data along with the surface graph of Tunnel diameter, soil cohesion, and the extent of settlement.

Using the constructed model, the article fulfilled to predict the settlement of Tehran subway line-3. ANFIS model made the surface settlement to 33.1 mm predicted.
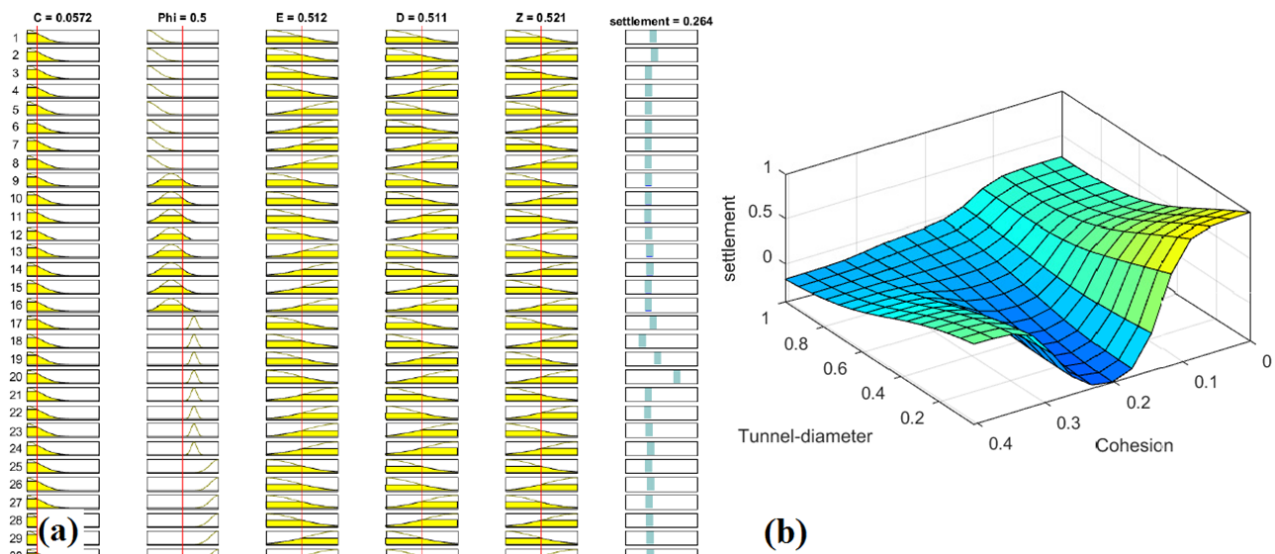


Fig. 6 (a) A Sample collection of rules of ANFIS and (b) surface graph of tunnel diameter, soil cohesion and the extent of settlement

## V. DISCUSSION

The study employed FLAC3D software and ANFIS to predict the amount of settlement in Tehran subway line-3. Table VI displays a chart of results obtained through various methods. The settlement actual values are recorded by the Surveying engineering team at ground level obtained.

ANFIS applies training algorithms of ANN and FL to design non-linear mapping between input and output spaces. Furthermore, because of its ability to combine linguistic power of a fuzzy system with numerical power of an ANN, this sys-tem is assumed to operate strongly in tunnel settlement modeling. The results of Table VI confirm this issue and indicate the better conformance of ANFIS against FLAC3D.

TABLE VI
TEHRAN NO.3 SUBWAY LINE TUNNEL RESULTS WITH DIFFERENT METHODS

| Method | FLAC3D | ANFIS | Measured |
|---|---|---|---|
| Settlement (mm) | 31 | 33.1 | 33.65 |

## VI. Conclusion

This article shows that computing intelligence is a good substitute for numerical modeling. However, using this intelligence method needs datasets of similar tunnels. Also, from the results of numerical modeling, it can be found that if the database is not in access, the results of numerical modeling can be reliable, and by using them, the crown and ground surface settlement can be analyzed and predicted.

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