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Numerical modeling of non-deformable support in swelling and squeezing rock

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ABSTRACT

Choosing the support system in swelling and squeezing rocks is one of the challenges for rock engineers. There are many factors that need to be considered such as support type, performance of the support, the support element, rock parameters, condition of the rock structure, and creating an appropriate support strategy. TH-type steel supports, which have long been used in deep underground mine headings, have recently started to be used as yield-control support system in tunnels. However, sliding ability of the TH steel support allows cross-section contractions. If the amount of convergence can not be calibrated, re-shaping studies have to be done at the excavated areas due to the occurrence of time-dependent creeps, especially in swelling and squeezing rocks. Also, numerical model studies for highly swellable and/or squeezable rocks must represent the time-dependent creep behavior of the rock. Simple stiffness parameters such as time-dependent creep, swelling index, and compression index should be addressed into the model. It is possible to constitute a high performance support system in this swelling and squeezing types of rocks by choosing appropriate round interval, using a non-deformable and heavier I profile and using sufficient parameters obtained by analysis. The present paper presents in-situ measurements and the analysis of time-dependent numerical model of non-deformable support system at the T-13 tunnel which is applied to one of the 39 tunnels at Eskişehir–Köseköy high-speed railway route.

1. Introduction

Deformation mechanisms are different in swelling and squeezing rocks. In both rock types, the pressure on the support is very high. The important issue is the performance of support under high pressure condition. If a support design can bear the high pressures derived from high deformation, it will be possible to excavate a tunnel without any damage. Of course, the pressures derived from high deformation cause some deformations on support system. However, the important thing for the designed support system is permitting to excavate tunnel safely by behaving in limits of calculated deformations.

Rocks containing clay minerals (especially clays in smectite group) swell when they interact with water; these rocks are called swelling rocks. Time-dependent convergence amount in underground structure put forward the effect of swelling. This convergence amount is related to water [1]. Swelling in tunnels generally happens at invert. High pressures derived from swelling cause occurring cracks at invert. The structural performance of the designed support system depends on two criteria: (i) sufficient bearing capacity under swelling pressure should not cause any discontinuities, (ii) there should be reasonable amount of deformations [2].

Squeezing rocks contain large amounts of clay. The harmless members of the kaolinite group and derivatives of the montmorillonites dominate the clay part of the rocks. The properties of the squeezing rocks change according to their contents [3]. According to Terzaghi [3], volume increase of the squeezing rocks, in behavioral definition, develops slowly without any sign. The squeezing is a large, time-dependent convergence along the tunnel excavation. Amount of the tunnel convergence depends on deformation ratio, friction region around the tunnel, and geological–geotechnical factors. Squeezing depends on time and friction. As it is mentioned above, squeezing is happened in long time and without a sign. If an ascendant support system is not established in this period, convergence amount in tunnel can reach extreme levels and support units can be damaged. Support system has to be established on time to prevent this. If there is any delay in support construction, the rock mass moves into the tunnel and new stress distributions occur around the tunnel [4]. There are important studies about this subject in the literature. The empirical [5,6] and semi-empirical [7], Aydan et al. [8], Hoek and Marinos [9] approaches attempted to clarify this subject in tunnel design. Each of these approaches, in itself, tries to identify the

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squeezing degrees of those rocks. The elasto-plastic models yielded unsatisfactory results for deformational effects under the condition of squeezing rocks at tunnel excavations [4].

Tunneling in weak rocks is very difficult especially in rocks consist of smectite group minerals like montmorillonite. When these types of rocks interact with air and water, they become highly deformable. Barla [4] indicated that this high deformation shows time-dependent creep behavior. These time-dependent deformations are examined by Wiesmann [10] in Simplon tunnel construction at Switzerland for the first time. Time-dependent creep behavior has been examined in detail by different researchers [3–15]. Common result of these studies is cross-section contraction according to time-dependent high deformations in the openings. Yassaghi and Salari-Rad [11] and Dalgıc [14] indicated that amount of deformation due to creep can change depending on geological condition, in-situ stress about rock mass strength, ground water flow, rock properties, and tunnel geometry. The support system at swelling and squeezing rocks can be designed to prevent the time-dependent deformations [16].

Support system in swelling and squeezing rocks can be designed with passive or active approaches. In the passive approach, deformation is allowed in tunnel walls and when deformation stops, re-shaping is done. Results of this situation are over-excavation, time loss, and increased labor cost. This type of problem can not be occurred in active approach. On the other hand, many parameters have to be analyzed simultaneously in detail. Otherwise, it results in more erroneous results than passive approach does. In both approaches, swelling or squeezing potential of the rock mass, excavation-support techniques, and adapted excavation sequence are important. Delay of support work at rocks which have high swelling or squeezing capacities, cause an increase in the deformation amount. Afterwards, rock mass moves into the tunnel and stresses around the opening disperse again until the rock fails. Excavated area needs to be exposed to as less air and water as possible; this is the most important factor. Extension of time will increase the deformations. Because, this type of rocks deform when they interact with air and water.

On the other hand, the pressures, occurred after tunnel excavation, are carried by tunnel face. With the advance of excavation, tunnel face loses its effect and deformations achieve the level of peak [17,18]. In this case, the round length becomes important. Even though the round length is one of the most important parameters in conventional tunneling, there is not a distinct method for the round length determination [19]. However, it was reported that the round length is effective on face collapse, non-supported opening and even support itself [20,21]. The round length is also very important to control deformations especially in rock which have high swelling or squeezing potential. According to Panthi [22] and Hoek [23], most of

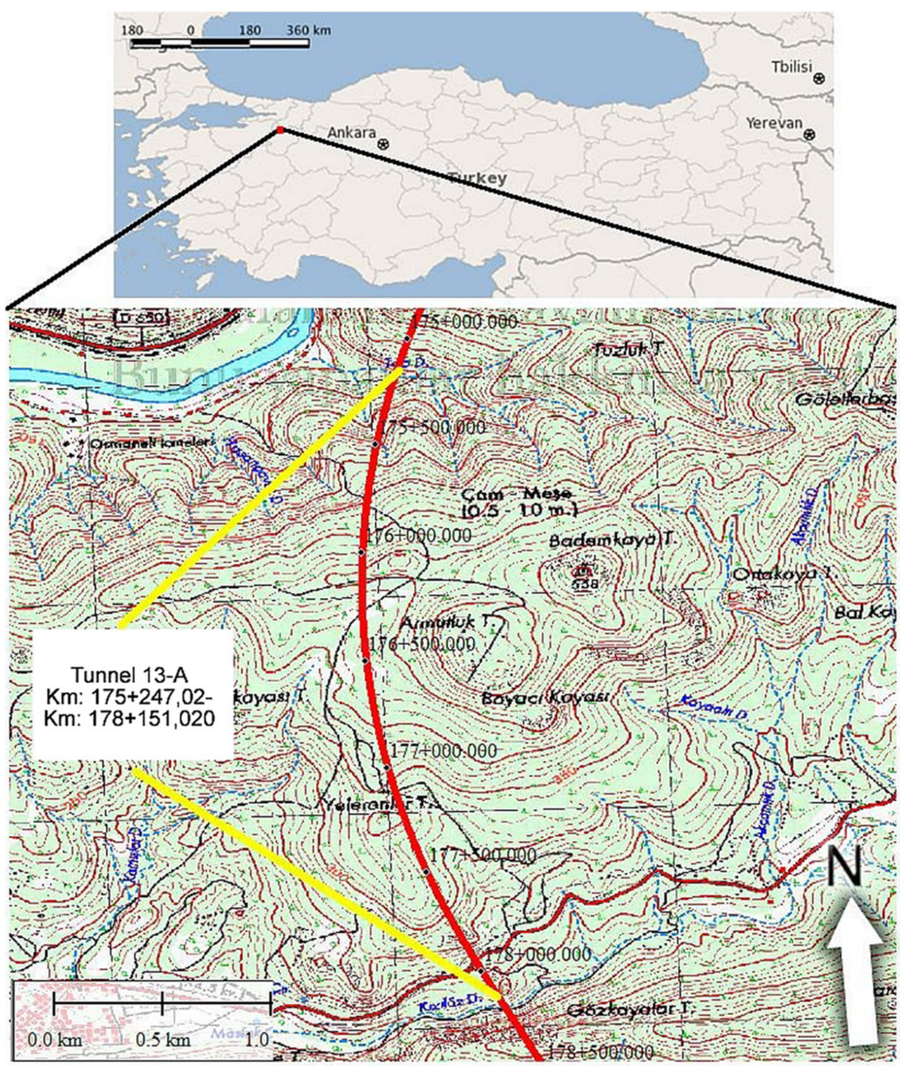

Fig. 1. Project description fault zones.

the deformations occur at two tunnel diameters distance behind the face. In this type of rocks, one of the most important studies to be done for support system design is predicting the swelling or squeezing amount and determining an excavation-support strategy. Only after choosing the strategy, it can be decided whether the support system is active or passive. It is available in the literature that "Yielding Support" system is applied in highly squeezable rocks latterly and positive results were achieved [24–27]. Contrary to these studies, in this paper, non-deformable support application in highly deformable rocks is discussed. As mentioned before, limiting the deformable behavior by cutting the interaction of the excavated area with air and non-deformable support application with certain excavation toleration is investigated. Finite Elements analysis was performed to see the time-dependent deformations and to examine the performance of non-deformable support. Soft soil creep model (Modified Cam Clay Model), which includes the time-dependent creep properties, was chosen as material model in the numerical model. Occurred face movements, bending moments on support elements, axial forces, and shear forces were determined and support performance was evaluated. When the model results and in-situ measurements, which were made after tunneling works, were compared, it was determined that non-deformable support system can be used in highly deformable rocks without need for making over-excavation.

2. Brief introduction of the project

The objective of the Ankara–Istanbul High-Speed Train Project is to reduce the traveling-time between the two biggest cities which are Ankara and Istanbul and increasing the percentage of railway in transportation by creating a fast, comfortable, and safe transportation facility. Köseköy–Inönü is the second phase of the Ankara–Istanbul High-Speed Train Project and has 158 km length which is designed as Section 1; 104 km (Köseköy–Vezirhan), Section 2; 54 km (Vezirhan–Inönü). The route gets through active fault zones and includes risky districts. View of the project and the seismic condition is given in Fig. 1 and engineering structures of the project is given in Table 1.

Table 1
Engineering structure of Ankara–İstanbul High speed Rail Project.

	Section 1	Section 2	Total
Length	104 km	54 km	158 km
Bridge	15 (1.170 m)	2 (200 m)	17 (1.370 m)
Viaduct	4 (2.247 m)	11 (6.582 m)	15 (8.829 m)
Tunnel	17 (17.100 m)	23 (21.966 m)	40 (39.066 m)
Open-cut tunnel	1 (219 m)	2 (1.360 m)	3 (1.610 m)

2.1. Geological and geotechnical conditions of T13–tunnel

T13 tunnel is planned 3580 m which starts at 175+240 km and finishes at 178+820 km. There will be four main groups of units in this tunnel. The information about formations passed in T13 is given in Table 2. Geological map of T13 tunnel is also given in Fig. 2. As seen in Table 2, both swelling and squeezing rocks excavated in T13 tunnel.

2.2. Laboratory tests on the samples from T13 tunnel

The most important parameters concerning rock engineers to design support systems in highly deformable rocks are: swelling and squeezing index of rock, liquid limit, plastic limit, plasticity index, cohesion, friction angle, elasticity modulus without drainage, and porosity. Swelling index, squeezing index, and creep index are needed to determine creep behavior during tunneling works. Calculation of these indices and other necessary parameters will be given in the next section. The Atterberg Limits, triaxial test, elasticity modulus, and poisson's ratio measurements and consolidation tests were conducted on samples taken from tunnel face of T13 tunnel. Information about tests is given in Table 3.

When obtained results from Atterberg limit tests, which are made for determining the sample's plasticity degree, were been put into the plasticity chart, it was determined that one of the samples was in inorganic clays group which indicates high compressibility and the other two were in inorganic clays group which indicate high plasticity. Plasticity chart was given in Fig. 3. Tables of triaxial shear tests made on every third sample were given in Fig. 3 and the graphics about elasticity modulus and Poisson's ratio was given in Fig. 4 [28,29]. XRD results made in Kütahya Dumlupınar University are given in Fig. 5. The XRD pattern was evaluated mineralogically using Inorganic X-Ray Powder Diffraction Index and PDF carts. As a result of this evaluation, smectite and illite minerals for clay group and quartz, feldspar, magnetite and opal-CT/ cristobalite minerals for non-clay group were determined.

3. Non-deformable support system analysis with time-dependent numerical modeling at highly deformable rocks

Convergence occurs at tunnel cross-section in elapsed time until the support is made after tunnel excavation. This deformation is less in strong and medium strong rocks. Besides, this movement is terminated by allowing convergence with certain toleration at weak rocks. This movement does not stop in a short time in high deformable rocks (especially clay, schist etc.) and deformation amounts are higher than the other rocks. Therefore, as a result of using inappropriate support, tunnel's cross-section is brought to its initial section with re-shaping studies. The important thing here is making support immediately after excavation. If this time span is shorter, rock mass are exposed atmospheric

Table 2
Geological and geotechnical definition of T13 tunnel [28].

Km	Lithology	Geotechnical information
175+240–176+550	Grafite–Schist (Pzpş)	Gray–dark gray, often–very often jointed schistosity planes slippery shiny, disintegrated partially, weak–very weak, chlorite schist and grays at upper parts. (Squeezing condition)
176+550–177+900	Claystone–Siltstone (Jkbd)	Red, red–brown–greenish black, gray often jointed, disintegrated partially, weak–medium strength, joints are open–close, slightly rough, wavy, clay and calcite fillings. (Swelling Condition)
177+900–178+500	Brecciated Limestone–Gravelstone–Sandstone (Tça)	Gray colored, coarse grained, medium –rare jointed, medium – thick layered, slightly disintegrated, very strong and competent. Joints are rough, wavy, dense coated, calcite and clay fillings partially
178+500–178+820	Gravelstone–Sandstone–Mudstone–Claystone–Siltstone (Tçk)	Yellowish-light brown, gray-greenish gray, close jointed, thin-medium layered, low-medium grade weathered, hard, high-strength-medium strength. Joints are open, waved, rough, colored with MnO and they include clayed embankment in some places.

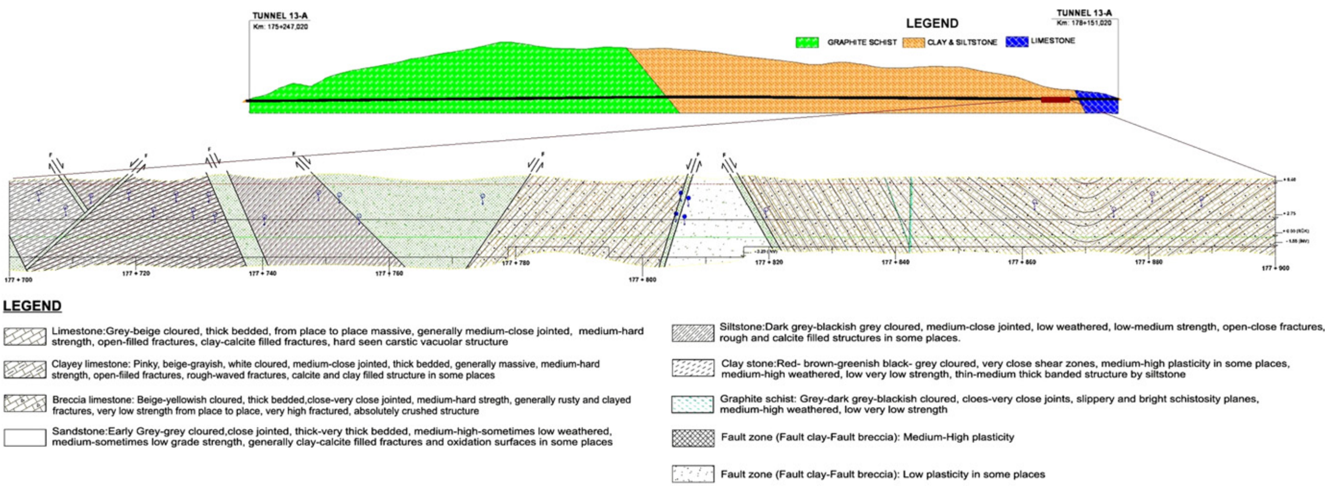

Fig. 2. Geological map of T13 tunnel direction [28].

Table 3
Results of the laboratory test [28,29].

	Sample 1	Sample 2	Sample 3
Elasticity modulus (MPa)	1240	1199	870
Possion's ratio	0,15	0,25	0,27
Liquid limit	56	65	187
Plastic limit	17	38	30
Plasticity index	39	27	157
Natural unit weigth (kN/m^3)	22,84	19,12	19,63
Dry unit weigth (kN/m^3)	20,69	14,67	15,57
Porosity (%)	20,70	44,19	40,09
Void ratio	0,26	0,79	0,67
Cohesion (kPa)	579	95	484
Internal friction angle (deg.)	19	18	0

conditions at minimum level. This situation decreases the swelling or squeezing capacity of the rock. However, time-dependent swelling and squeezing properties of the rock must be considered in support analysis. Support designs which are made only with failure criterions will be insufficient. Consequently, creep properties of the rock needs to be integrated into the model in numerical modeling studies.

In this study, the analysis of non-deformable support system of T13 tunnel in oily clays at Eskişehir–Köseköy high-speed railway route was made using Finite Element Method. The analyses were made in PLAXIS 3D Tunnel V2. Soft Soil Creep Model was used as material model. In other words this model's (also known as Modified Cam Clay Model) failure criterions were same as Mohr–Coulomb Model's (cohesion, friction Angle and dilatancy angle). The basic stiffness parameters are Modified Swelling Index (κ^*), Modified Compression Index (λ^*) and Modified Creep Index (μ^*):

$$\lambda^* = \frac{C_c}{2.3(1+e)} \tag{1}$$

$$\kappa^* \approx \frac{2.3C_r}{2.3(1+e)} \tag{2}$$

$$\mu^* = \frac{C_\alpha}{2.3(1+e)} \tag{3}$$

3.1. Problem definition

The first phase of the system used at excavation-support work is shown in Fig. 6. Under this condition, at tunnel excavation, up to 63.4 cm convergences occurred in time in the area of smectite group clays and high deformable formations at T13 tunnel of Ankara–Istanbul high-speed railway route. The most important reason for this that the elapse time for closing support ring is so long. As a result of this, re-shaping works are made because these convergences are out of tunnel tolerations. An example of deformations before re-shaping application at T13 tunnel is given in Fig. 7 and time-dependent vertical convergence measurements are given in Fig. 8.

3.2. Numerical modeling for the non-deformable support system with soft-soil creep model (modified cam-clay model)

Re-shaping after these types of deformations in tunnel constructions is considerably expensive and time-consuming. Therefore, it is considered that analyzing a non-deformable system for a support design in the same formation is a requirement. 3D numerical modeling is the most convenient tool for the partial excavation support analyses in formations that have high deformability properties.

As mentioned above, high deformable rocks suppose to represent with Soft Soil Creep Model (modified Cam-Clay Model). In this model, there must be Mohr–Coulomb parameters: cohesion, internal friction angle, and dilatation angle. However, it is not possible to define model only with these parameters. For this reason, parameters including swelling and squeezing properties of the rock must be integrated into the model. Soft Soil Creep Model includes all of these parameters.

The field studies (drilling, geotechnical investigations etc.) and the designed support system elements, which are used for analyzing a higher performance support system to achieve this problem, are given in Table 4.

In this numerical model, the swelling and squeezing data and the Mohr–Coulomb parameters of the rock mass were used. Case studies about face bolt and pipe applications used in this model are available in literature and Plaxis handbook [30,31,32,33,34,35,36]. Data used at modeling stage are given in Tables 5 and 6, respectively.

The main objective of developing this numerical model is examining the performance of the support system which will apply with time-dependent creep properties of rock. For this purpose, the numerical analysis was made for a period of 816 days. Seven hundred days of this time includes the period of developing until it stops. Remained time includes the excavation and support stages. The integrated construction stages are given below.

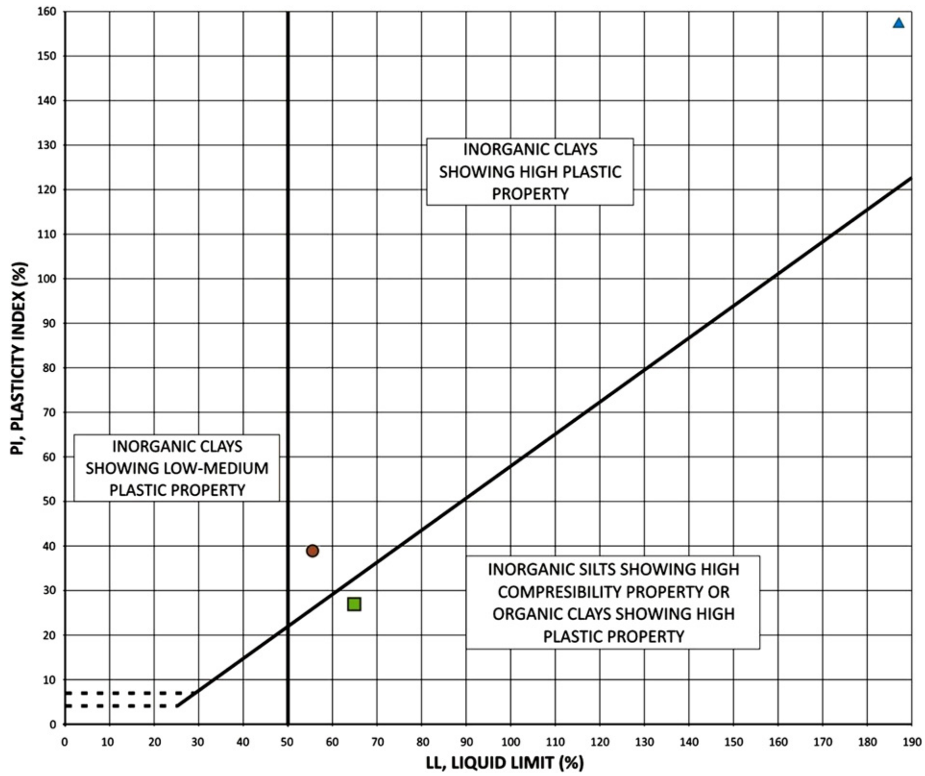

Fig. 3. Test results on the plasticity chart [29].

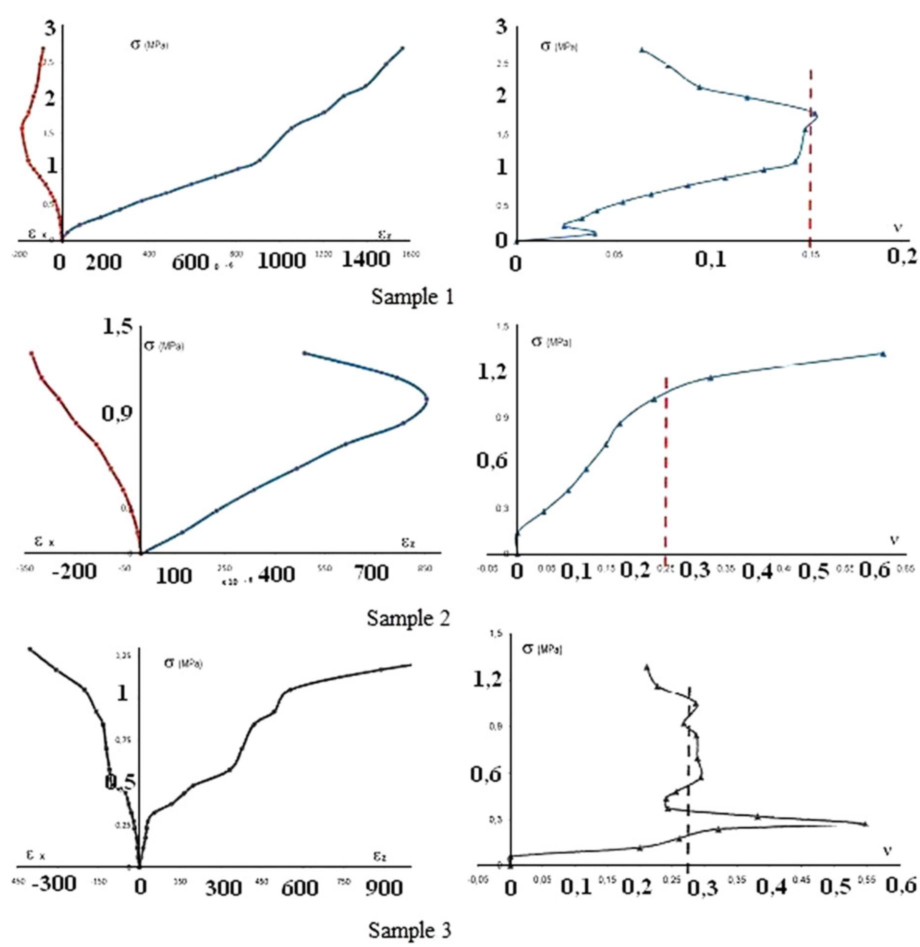

Fig. 4. Elasticity modulus and Poisson's ratio graphics of the samples [29].

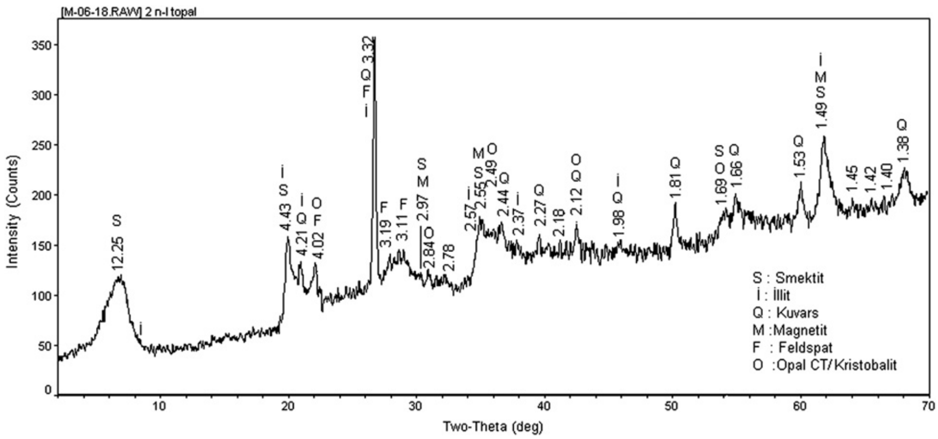

Fig. 5. XRD results.

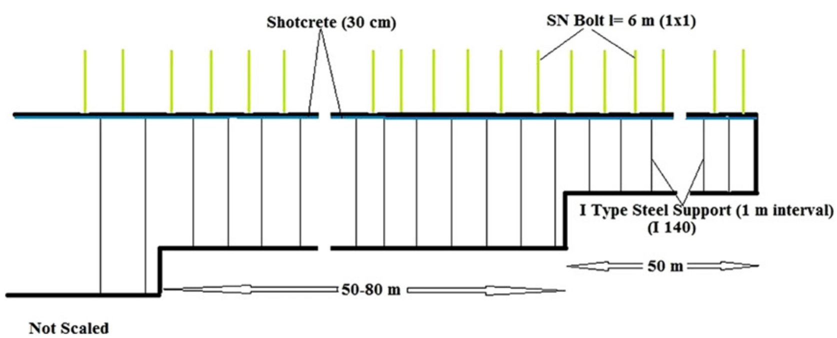

Fig. 6. Support system of T13 tunnel before non-deformable support application.

Fig. 7. The view of the deformed T13 tunnel.

1. Stage: Installing the model
2. Stage: Reset displacement to zero
3. Stage: Defining the excavation of tunnel, steel pipe, temporary invert, face bolts, invert concrete, face concrete, IBO bolts
4. Stage: 1 m crown advance
5. Stage: Applying the support of crown
6. Stage: 1 m crown advance
7. Stage: Applying the support of crown
8. Stage: 1 m bench advance
9. Stage: Applying the support of bench
10. Stage: 1 m bench advance
11. Stage: Applying the support of bench
12. Stage: 1 m invert advance
13. Stage: Applying the support of invert
14. Stage: 1 m invert advance
15. Stage: Applying the support of invert
16. Stage: Applying 2 m invert concrete

In order to prevent high amounts of deformation, invert support has to be made as quick as possible. Another important parameter is the distance between invert support and excavation face. This distance needs to be long enough to provide comfortable work environment and short enough to limit the deformations. The supports of the tunnel sections (crown, bench, and invert) which are made in appropriate distance and time, would stabilize the tunnel. So that high deformation occurrence could be prevented and high pressures derived from high deformation would be obstructed. That is the reason for some construction stages were

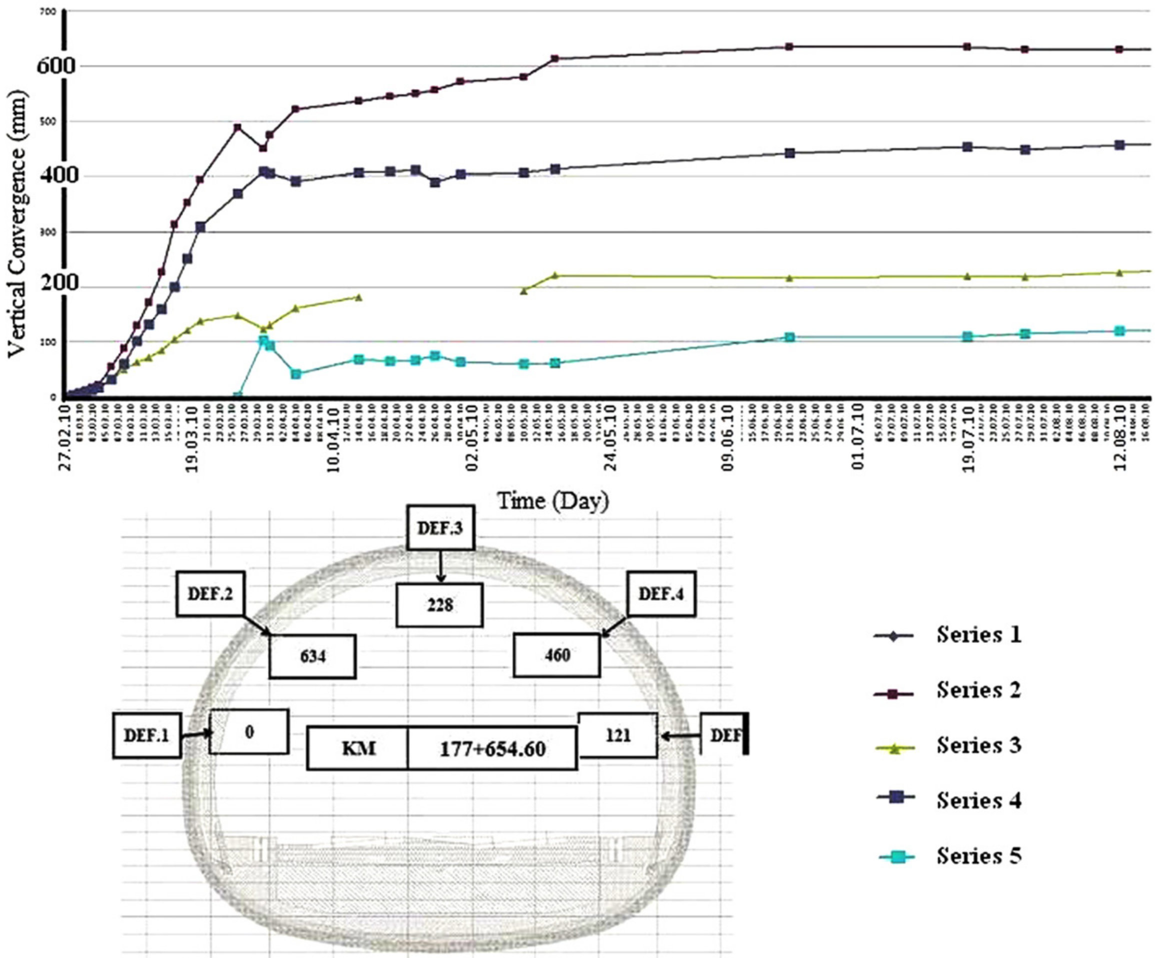

Fig. 8. Time-dependent convergence measurement at T13 tunnel.

Table 4
Non-Deformable support system and element properties.

Support element	Properties
Steel support	I 200 Profile (1 m)
Shotcrete	40 cm
Bolt	IBO (l=8 m and 1 × 1 m)
Pipe	6 m (2 in., overlap= 3 m)
Top heading temporary invert	40 cm
Face bolts	10 unit (12 m, overlap= 3 m)
Face shotcrete	10 cm
Invert concrete	3,15 m

Table 5
Properties of rock and structural elements.

Rock properties	
Unsaturated unit weight, γ_{unsatut} (kN/m^3)	20,690
Saturated unit weight, γ_{sat} (kN/m^3)	22,840
Modified swelling index, κ*	00,283
Modified compression index, λ^*	00,324
Modified creep index, μ**	00,016
Poisson ratio for unloading-reloading, ϑ_{ur}	15
K_0^{NC}, $\frac{\sigma'_{xx}}{\sigma'_{yy}}$ stress ratio in a state of normal consolidation	0,611
M, K_0^{NC}-related parameter **	0,735

* λ^*/μ^* is in the range between 15 and 25

** $M = 3\sqrt{\frac{(1+K_0^{NC})^2}{(1+2K_0^{NC})^2} + \frac{(1-K_0^{NC})(1-2\vartheta_{ur})(\lambda^*/\kappa^*-1)}{(1+2K_0^{NC})(1-2\vartheta_{ur})\lambda^*/\kappa^*-(1-K_0^{NC})(1+\vartheta_{ur})}}$

repeated. Vertical in-situ stress ($\sigma_{v,0}$) applied to the model boundaries was assumed to be equal to overburden stress. The initial horizontal stress ($\sigma_{h,0}$) is related to the initial vertical stress by the coefficient of lateral earth pressure (k), ($\sigma_{h,0} = k^*\sigma_{v,0}$). As boundary condition, model size was defined three times longer than the tunnel's size to prevent tunnels from the boundary condition.

Total deformation, total stress, bending moment, and axial forces of applied numerical model are given in Fig. 9.

3.3. *Application and field measurement for the non-deformable support system at T13*

While passing the high deformable formation in T13 tunnel, high deformations occurred and the repairing and the re-shaping operations became an expensive work. Also, tunnel safety decreases. Instead of these time-consuming and expensive works, analysis of non-deformable support system was made. As the result of the analyses and calculations, it is considered to use the support system mentioned above. Cross-section of the tunnel during application is given in Fig. 10.

In-situ convergence measurements are made during the non-deformable support system application in T13, which is highly compressible. The convergence measurements are given in Fig. 11.

The deformation measurements, which were taken before non-deformable support system, were given in Fig. 8, which illustrates an important deformation (about 50 cm), within first 20-day period after the implementation of the support. An ongoing process, the amount of deformation increases up to 63.4 cm. Due to the high deformations

Table 6
Properties of structural elements.

	Type	EA (kN/m)	EI (kNm^2/m)	w (kN/m^2)	ϑnu (–)
Shotcrete and top heading temporary invert	Elastic	13,280,000	177,066	9,6	0,15
Steel pipe	Elastic	143,884	38	32	0,15
Face bolt	Elastic	45,396	–	–	–
IBO bolt	Elastic	56,700	–	–	–

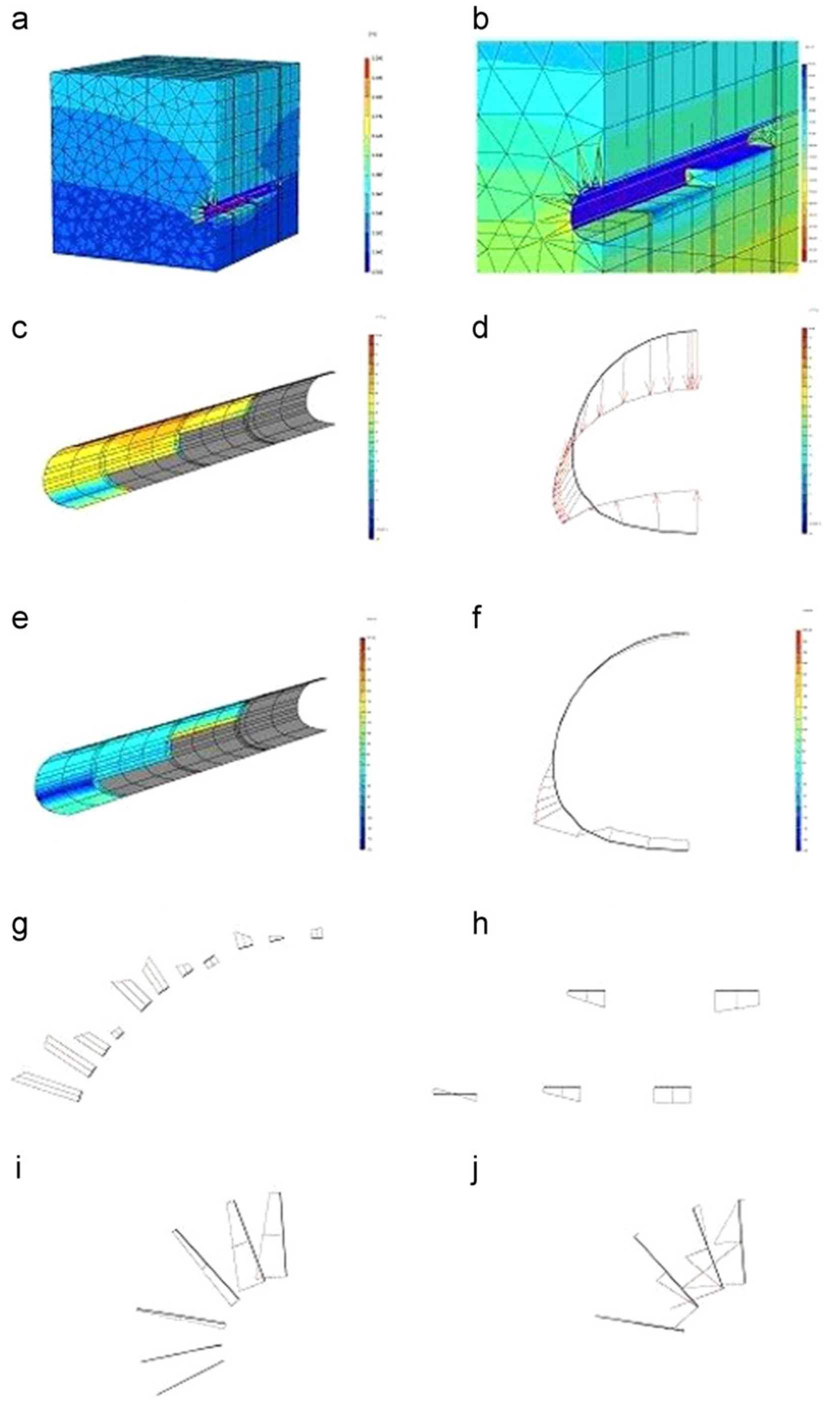

Fig. 9. Results of the soft soil creep (modified cam-clay model) model analysis (a) total deformation; (b) total stress of model; (c) and (d) total deformation of support (maximum 78,13 mm); (e) and (f) bending moment on the support (maximum 3090 kN/m); (g) axial forces on the steel pipes (max. 62,93 kN/m); (h) axial forces on the face bolts (29,79 kN/m); (i) axial forces on IBO bolts (a) top and bench (99,83 kN/m); (j) axial forces on IBO bolts only top (203,69 kN/m).

and fractures encountered in support, it is decided to use new and heavier support system. The most important aim of this system is to close the support ring as soon as possible in the vicinity of the work. A numerical model with soft soil creep model was done to query the performance of the new and heavier support system. According to the results obtained from the developed numerical model, it was forecasted that there will be 4.813 cm deformation. Therefore, excavation tolerance rate was selected as 10 cm. Following the construction of newly applied non-deformable support, deformations were monitored over time. Analyzing the deformations seen in Fig. 11, approximately 7.8 cm deformations were seen. Since this value is within a predetermined convergence tolerance for the excavation, it does not constitute a problem.

4. Results and discussions

The meaning of the "non-deformable" support is not the supports without any deformation. The main purpose in these supports is keeping the deformation in permitted levels. Otherwise the re-excavation work, which is generally encountered at "yielding supports", may arise. Determining the support units in this system needs experience. Determining the time-deformation characteristic of the excavating rock mass precisely is one of the most important keys to design the accurate support system. To set up a redundant rigid support system can cause damage on support units because of the occurred pressures. In the designed system, minor and negligible fractures at concrete constitute a relief zone for the pressures and induce relieving on the support. It is determined by long-term in-situ observations that there is not any development seen in these fractures.

Extreme deformations in T13 tunnel, opened in high deformable rocks, make re-shaping works mandatory. Due to those time-consuming and expensive works, it is decided to define field better and make a new support design. The expectation from the new design is keeping deformations within tolerance. Accordingly, information both from laboratory tests of samples and from swelling-squeezing behavior of the rock were used. However, making support design is very difficult in this type of rock masses. For this reason numerical modeling was chosen as the best solution. Model analyses are made many times during the determining the behavior of the rock mass and calibrating of the model, sticking to the flow chart suggested by Feng and Hudson [37]. 4.813 cm deformation was observed in the numerical modeling results. The bending moment affecting the support system is maximum 3090 kN/m, axial force on steel pipes is 62.93 kN/m and axial force on face bolts is 29.79 kN/m. Axial force on IBO bolts at bench part is 99.83 kN/m and at crown part 203.69 kN/m. According to these results, it was determined that new suggested non-deformable support system was stable and it was in deformation tolerances.

Extreme deformations in tunnel were not observed at in-situ convergence measurements. However, little cracks at both sides of the bench part were observed during in-situ observations.

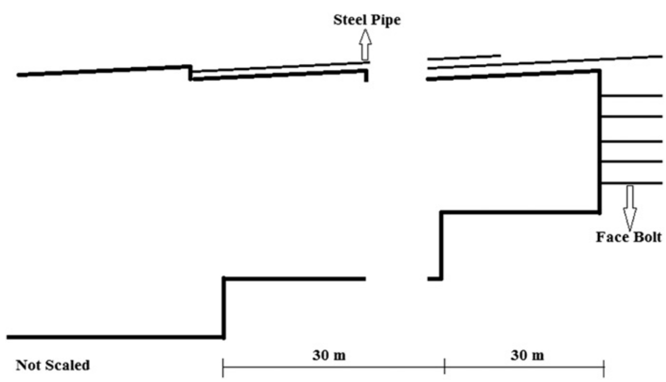

Fig. 10. Cross-section of tunnel during the non-deformable support application.

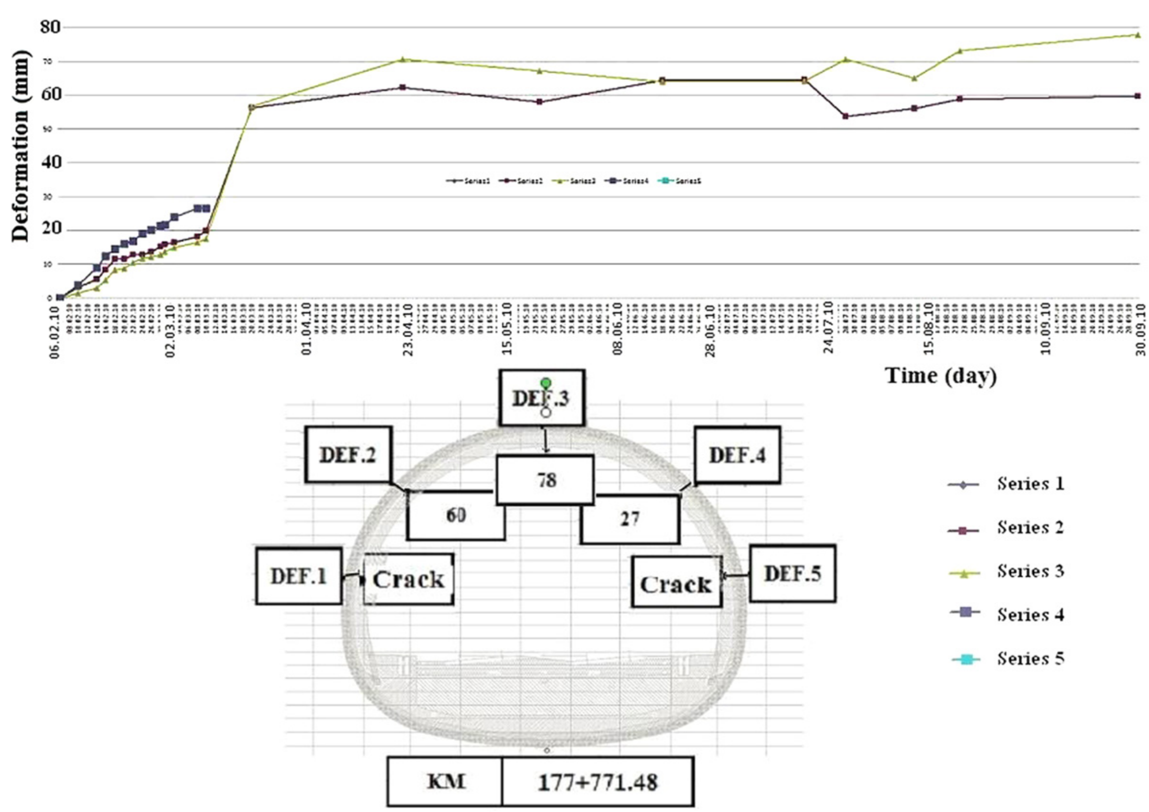

Fig. 11. In-situ convergence measurement in T13 Tunnel during non-deformable support applications.

These cracks were observed in time but no progress is determined. It was considered that the most important reason of these cracks was the stress concentration.

The numerical modeling results and in-situ convergence measurement results were very close to each other. After applying the non-deformable support system, some problems occurred occasionally but a re-shaping was not needed.

5. Conclusions

It is very difficult to make support system for tunnels in swellable and squeezable rocks. Many parameters have to be considered together. Swelling and squeezing behavior of the rock should be evaluated in the design unlike classic rock support design. Therefore, the most important tool is the numerical modeling. However time-dependent deformation behavior of the rock is needed to be defined correctly. A numerical model that includes only the Mohr–Coulomb parameters (cohesion, internal friction angle and dilatation angle) is not sufficient for a support system design in this type of rocks.

Latterly, using steel support that allows deformation in this type of rocks has given good results. It is accurate to analyze again for every rock medium in the support systems that allow deformation. When it is decided to use deformable support system in the tunnel, it is a requirement to make re-shape. Especially in large-scale tunnels for railways and roadways, deformations will be larger. This means much more re-excavation and re-setting the support. It is determined that re-shaping in this type of a tunnel in Turkey increases the excavation-support costs up to 15–20%.

In the other alternative, there is no re-shaping work in non-deformable support suggestion. Works continue in a routine and no time loss for re-excavation. However, one should be very careful in non-deformable support design. Time-dependent deformation features of the rock mass should be determined accurately. If only these parameters are determined accurately, the performance of non-deformable support system will be high. As it is done in this study, numerical modeling is the most important tool to give information about non-deformable support system performance.

It is determined in this study that re-shaping works made after extreme deformations are too expensive and time-consuming. Consequently a heavier and non-deformable support system is applied. The performance of the support system is confirmed with numerical model and it is compared with the in-situ measurements. It is seen that results of the numerical model and in-situ measurements are very close to each other.

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