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Discontinuity Controlled Deformation Estimation in Small Diameter Tunnels

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Abstract: Tunnel projects are carried out in tunnel construction by evaluating the soil and rock profiles obtained from the exploration drillings along the route, groundwater level, and structural elements. In practice, there are some differences between the geological sections foreseen according to the exploration drillings and the structural elements encountered during tunnel construction. This study has modeled a tunnel, through intermediate to weak and very weak rocks, between Ankara and Istanbul, obtained the deformation amounts by numerical analysis. To get the principal stresses, deformation forces, and surface settlements on the tunnel lining in each excavator were used Phase2D. The total displacement amounts were calculated with the numerical analysis. After, during tunnel manufacturing, were measurement deformations to control projects' adequacy. Thus, the results of the analysis and deformation amounts encountered during the tunnel between Ankara and Istanbul opened were compared. At the end of the study, when the discontinuity properties are taken into account in the calculation, it was seen that the deformations obtained and the deformations obtained from the numerical analysis gave very close values. As a result, it was concluded that discontinuity data that was not seen at the project stage for cost-effective tunnel design in tunnels should be collected and added to the analysis as much as possible. It was concluded that corrections should be made in the support system during the manufacturing studies with the back analysis method.
Keywords: Tunnel, Deformation, Numerical Analysis, Discontinuity

Küçük Çaplı Tünellerde Süreksizlik Kontrollü Deformasyon Tahmini

Öz: Tünel inşaatlarında güzergâh boyunca yapılan araştırma sondajlarından elde edilen toprak ve kaya profilleri, yeraltı suyu seviyesi ve yapı elemanları değerlendirilerek tünel projeleri gerçekleştirilmektedir. Uygulamada, araştırma sondajlarına göre öngörülen jeolojik kesitler ile tünel inşaatı sırasında karşılaşılan yapısal elemanlar arasında bazı farklılıklar bulunmaktadır. Bu çalışmada Ankara ile İstanbul arasında orta-zayıf ve çok zayıf kayaçlarda bir tünel modellenmiş ve sayısal analiz ile deformasyon miktarları elde edilmiştir. Her bir kesitte tünel kaplaması üzerindeki asal gerilmeleri, deformasyon kuvvetlerini ve yüzey oturmalarını elde etmek için Phase2D kullanılmıştır. Sayısal analiz ile toplam yer değiştirme miktarları hesaplanmıştır. Ardından tünel imalatı sırasında projelerin yeterliliğini kontrol etmek için deformasyon ölçümleri yapılmıştır. Böylece Ankara-İstanbul arasında açılan tünelde karşılaşılan deformasyon miktarları ve analiz sonuçları karşılaştırılmıştır. Çalışma sonunda süreksizlik özellikleri hesaplamada dikkate alındığında elde edilen deformasyonlar ile sayısal analizden elde edilen deformasyonların birbirine çok yakın değerler verdiği görülmüştür. Sonuç olarak tünellerde maliyet etkin tünel tasarımı için proje aşamasında görülmeyen süreksizlik verilerinin mümkün olduğunca toplanarak analize eklenmesi gerektiği sonucuna varılmıştır. İmalat çalışmaları sırasında destek sisteminde geri analiz yöntemi ile düzeltmelerin yapılması gerektiği sonucuna varılmıştır.
Anahtar Kelimeler: Tünel, Deformasyon, Sayısal Analiz, Süreksizlik

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1. Introduction

Today, tunnel construction has increased worldwide with the increasing transportation and energy sector with the advances of technology and industry. One of the underground structures is a field where different disciplines work together because it includes engineering geology, rock mechanics, and soil mechanics. In this study, tunnel construction is very difficult to make a project due to its complex geological history, geometry, loads and different soil and rock properties. It is important to have a detailed and correct interpretation of geological data, mainly because of working of materials with different soil and rock properties. Otherwise, significant difficulties are encountered in tunnel construction. For example, almost one-third of Japan is covered with tertiary sedimentary rocks of volcanic origin. Many highways and railways have been already constructed or built-in such rocks. It is significant the squeezing potential of rocks and the selection of appropriate means of reinforcement and excavation techniques in such rocks due to the presence of such rocks, primarily due to the increased number of squeezing tunnels. Consequently, tunneling was mainly due to the squeezing of the surrounding media exhibit large deformations during excavations in expansive rocks. Another example is the difficulties met by the two open TBM's (Atlas Copco), excavating from the North Portal is composed of sandstone and marl layers. During tunneling, with the worsening of the rock mass conditions and the reduced stand-up time, instability of the tunnel circumference started to occur immediately after excavation, so it has been the necessary installation of a nearly continuous form of support close to the face. A tunnel was constructed for the Maneri hydel (hydro-electric) project on the River Bhagirathi through quartzitic and metabasic rock formations of the young Himalayas. During tunneling, problems of tunnel face collapse, cavity formation, and large tunnel closures leading to buckling of steel ribs on account of squeezing ground conditions were encountered. This state was seen as the absence of advanced knowledge of the frequently changing rock mass and groundwater conditions and, therefore, the inability of the tunneling engineers to modify the construction method and the support system [1-4].

From geological investigations, we can list the origin and current state of rocks in the tunnel region or its axis, explanation of structural anomalies, determination of ground water and gases, estimation of the temperature regime in the tunnel during excavation and changes in natural stresses depending on geological events [5]. Then, it is necessary to evaluate this information and the results of the drilling studies together. After the excavation begins, geological investigations are continued. In this way, it is ensured that the rock properties are examined on-site, especially the cracks are measured and the environment is predicted in future sections. However, it is an important point to have the advantage of observing and measuring cracks on-site and making changes in support systems when, it is necessary.

Because of complicated soil or rock geology, tunneling construction can always present many problems, especially in squeezing ground. Compression is a phenomenon produced by plastic flow, which can last for a long time when the limiting shear stress in the rock mass around the tunnel is exceeded and produces large deformations around the tunnel [6-7]. It requires non-standard excavation and support methods such as re-excavation or excessive bracing during and after construction where the prescribed threshold is exceeded. The Bolu tunnel, Anatolian Motorway, Turkey, can be an example of tunneling in a squeezing rock can. In this tunnel, low-angle thrust faults negatively affected the tunnel stability, and the design of the Bolu tunnel was revised several times construction. Even tunnel manufacturing was stopped for a year. A flexible support system was applied in the thrust zone. However, because this flexible support allows large deformations to occur, the Elmalık right tube of the tunnel collapsed partially. Hence, the application of the flexible support system was abandoned later. Instead, more heavy support systems were used, and as a result, deformations were controlled. Another tunnel problem was seen that the Yacambú-Quibor tunnel in the State of Lara in Venezuela. The tunnel transfers water from the wet tropical Orinoco basin, on the eastern flank of the Andes, to semi-arid Quibor valley on the western side of the

Andes. Severe squeezing problems during the tunnel's construction presented many challenges to the project. Firstly, the problem was in very weak graphitic phyllites at depths of up to 1270 m below the surface. Initial attempts to use an open-face TBM in 1976 failed, as did attempts to use heavy support to resist squeezing. Difficulties continued with floor heave in sections of the tunnel in which horseshoe profiles were used, even after the introduction of yielding support. Over the 32 years of construction, approximately 30 different support designs were used and, in better rock conditions under moderate stress conditions, many of these designs were successful. In Saint Martin, access adit along the Base Tunnel of the Lyon-Turin railway link was encountered squeezing conditions during excavation in the Carboniferous Formation. Several support systems were used in the Carboniferous Formation. However, it soon became apparent that stiff support would not be feasible in the severely squeezing conditions encountered. Initially implemented support system consisted of face reinforcement, steel ribs with sliding joints, anchors, and a thin shotcrete layer in a horseshoe profile. Finally, encountered this case, an innovative tunnel construction method was introduced in which couples face reinforcement using fiber-glass dowels with yield-control support. In tunnel-34 of the Ankara-Istanbul high-speed railway project at a length of 2218 meters, a Non-deformable support system (NDSS) applied to the problems (excavated with NATM method), which is driven in graphite schist, was used. NDSS presence can give time-dependent solutions and deformations within the calculated deformation limits rather than zero-deformation. Tunnel safety is an essential prediction of deformation while tunnel support design works. Hoek and Brown (1980), Brady and Brown (1990), and many more researchers have published equations for calculating the stiffness and capacity of different support systems [7-11].

During tunnel planning and design, stability measures should be established to minimize stability problems during fabrication and optimized support. The most important basis in this planning is to determine the tunnel excavation face's behavior, the stresses in front of the tunnel excavation face, and the measures for these effects [12]. The easiest way of solutions is numerical modeling today. There are many methods in numerical modeling. The most popular are Finite Elements, Finite Differences, and Boundary Elements [13]. Feng and Hudson [14] examine numerical modeling under two headings as advanced modelling and backward analysis method; (1) advanced analysis: it provides an assessment with the data obtained before the project starts and can be discussed in more detail during the project process (2) Back analysis and back analysis notifications: It is done for reasons such as calibration of the design, parameter back analysis, hazard estimation, redesign, and advanced analysis during manufacturing in underground openings.

High deformation is not expected in conventional tunnel solutions in narrow-section tunnels causes the manufacturing tolerances to be kept at a minimum. It also includes the problems encountered in determining the characteristics of the units that do not give surface. Although the unit properties are determined by geotechnical drilling, the continuity of discontinuities creates problems in the correct definition of features such as direction and slope, filling type and condition. In this study, the deformations determined by advanced analysis and occurred during the fabrication in the narrow section tunnel opened in three different rock conditions (very weak, weak and intermediate) were examined. It has been determined that the amount of compaction predicted and actualized in weak and very weak rock conditions remained within acceptable limits. Still, serious differences occurred in clastic or medium rock, in other words. The input deficiencies in the numerical analysis were examined with the back analysis method.

2. Work Area and General Features

There are 36 tunnels of different lengths (varying between 200 m-6100 m) with properties ranging from weak to solid rock on the Ankara-Istanbul High-Speed Train line, where the study was conducted. In the line where transportation activities started in 2014, to ensure the safety, 16 security tunnels were designed for 11 main tunnels longer than 1000 meters by the UIC [15] standard. This study focuses on the T35-GT2 tunnel, which has not been studied before and has different geological conditions (in moderate-weak and very weak rocks) compared to other safety tunnels in the T35 tunnel located at the border of the old and young units. T35-GT2 tunnel route is situated between Bozüyük district and İnönü district, one km west-southwest of Bozüyük (Fig. 1). The thickness of the cover over the tunnel varies between 10 and 86 meters and is 224 meters long. The railways' security tunnel section was 4.5 meters wide and 5 meters high, considering the fire brigade passages in an emergency. As shown in Fig. 2, it has a horseshoe cross-section and was opened by a conventional method.

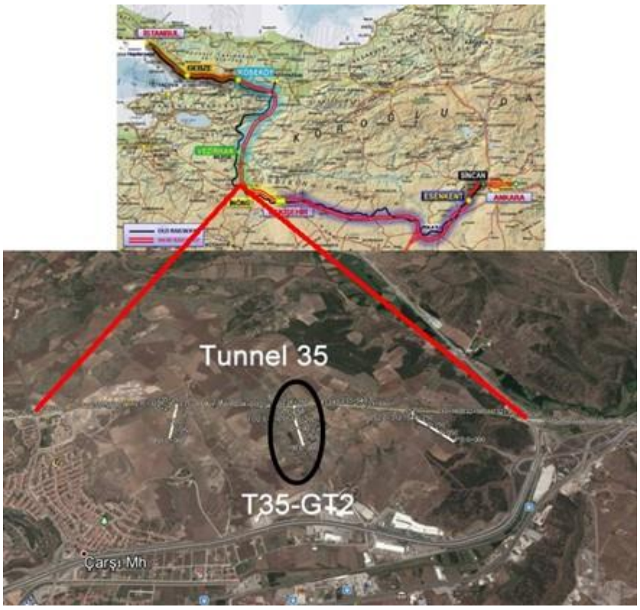

Figure 1. Satellite image of T35 and safety tunnels.

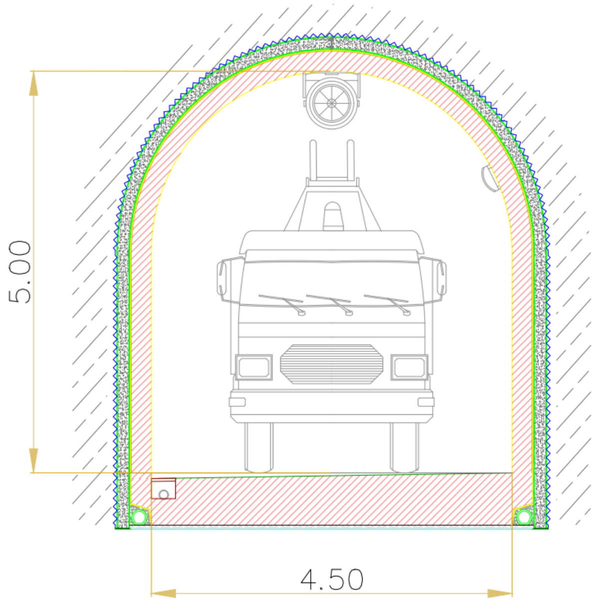

Figure 2. Security tunnel type section.

2.1 Geological and Geotechnical Properties

With the field and drilling works carried out along the T35-GT2 tunnel, starting from the entrance part of the tunnel, the Miocene aged Porsuk Formation, very weathered levels of Bozüyük Granitoid and Bozüyük Granitoid units will be passed (Fig. 3). The Porsuk Formation, located at the tunnel entrance and consists of less anchored conglomerate, sandstone and siltstone units, comes with an angular unconformity over the Bozüyük Granitoid underlying it [16].

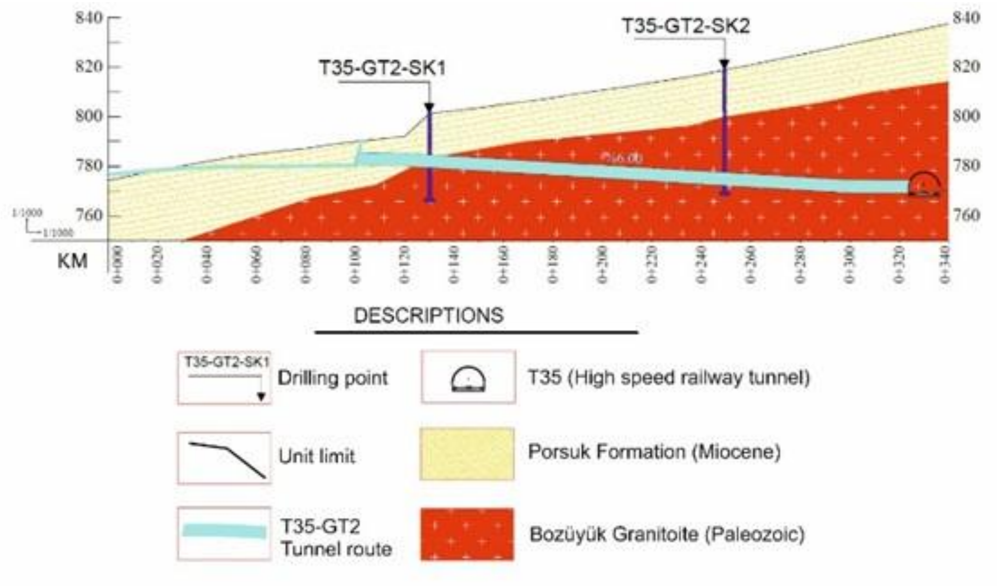

Figure 3. Geological map of T35-GT2 tunnel direction.

Figure 4. Geological units to be encountered in T35-GT2 (a: Porsuk Formation claystone, siltstone unit (Bozüyük) crossed at T35 b: Very weathered Bozüyük Granitoid passed through tunnel no 35 c: Cut with hydrothermal quartz and pegmatite veins in different thickness-position “Bozüyük Granitoid”(T35 entrance portal east section, highway cut)).

These units gain the feature of weak-strength rock in places (Figure 4a). After the Porsuk Formation, "Bozüyük Granitoid" units will be cut. Bozüyük Granitoid shows different physicochemical properties throughout the tunnel. Near the surface, it indicates very weathered, weak, very fractured-cracked features, while it indicates moderately weathered, moderately solid, moderately fractured-cracked structure towards deep (Fig. 4b).

It is distinctive with its multi-foliation structure and cataclastic appearance. Besides, it is cut by hydrothermal quartz veins of different thicknesses (10 cm to> 10 m) and positions (Fig. 4c). The geological units in the tunnel line are ISRM [17] and Q [18], RMR89[19], NATM [20], and GSI [21], which are widely used in tunneling. It was aimed to determine the appropriate front support type according to NATM by examining the rock masses according to their classification (Table 1).

Table 1. Evaluation of geological units according to their discontinuity properties and rock mass classification systems.

Discontinuity Features	Porsuk Formation	Weathered Bozüyük Granitoid	Bozüyük Granitoid
Discontinuity Sets	3 Joint sets	3 Joint sets	2 Joint sets
Discontinuity spacing (m)	0.13	0.35	0.43
Description (ISRM, 2007)	Close Spacing	Moderate Spacing	Moderate Spacing
Persistent of discontinuity (m)	25.59	22.45	7
Description (ISRM, 2007)	Very High Persistent	Very High Persistent	Medium Persistent
Discontinuity Roughness (JRC)	1	1	3
Discontinuity Aparture (mm)	7	6	1,70
Description (ISRM, 2007)	Moderately Wide	Moderately Wide	Open
Degree of weathering of discontinuity surfaces	W4	W4	W3
Seepage	1	1	1
Description (ISRM, 2007)	The discontinuity is very tight and dry, water flow aiong it docs not appear possible.	The discontinuity is very tight and dry, water flow aiong it docs not appear possible.	The discontinuity is very tight and dry, water flow aiong it docs not appear possible.
Rock Quality Designation (% RQD)	10	19,7	35
Description (Deere, 1964)	Very Poor	Very Poor	Poor
Q	0,018	0,02	0,519
RMR 89	18	20	39
GSI	20	25	40
NATM (1994)	C-2	C-2	B-3

Table 2. Physico-mechanical and elastic properties of rock samples belonging to geotechnical units.

Physico-Mechanical and Elastic Properties		Porsuk Formation (n=11)	Weathered Bozüyük Granitoid (n=8)	Bozüyük Granitoid (n=11)
Unit Volume Weight (kN/m^3)	Max	0,25	0,27	0,26
	Min	0,21	0,21	0,21
	Average	0,22	0,23	0,22
Uniaxial compressive strength, (MPa)	Max	17,13	27,23	57,35
	Min	5,17	4,35	23,45
	Average	9,22	20,25	42,3
Elasticity Modulus (GPa)	Max	3,43	2,17	10,54
	Min	0,22	7,98	0,61
	Average	0,4	5,02	2,5
Poisson's Ratio	Max	0,33	0,36	0,33
	Min	0,27	0,27	0,27
	Average	0,3	0,3	0,31

In addition, related experiments were carried out in the laboratory to determine the physico-mechanical and elastic properties of the geological units with samples taken from 2 drillings on the tunnel route (Table 2).

2.2 Rock Mass Parameters Used in Numerical Analysis

The units on the tunnel route show rock behavior. For this reason, the Generalized Hoek-Brown failure criterion was preferred in numerical analysis. With the help of this method developed for jointed rock environments, the Hoek-Brown criteria to be used in numerical analysis are determined from the existing rock material and rock mass parameters [22]. Geological Strength Index (GSI), Hoek-Brown coefficients (mb. mi. s, a), the rock mass parameters, and the deformation modulus of the rock mass are the critical parameters used in the analysis. The GSI value for the studied rock environments Hoek [23], Hoek et al. [24], and the quantitative GSI Table reviewed and developed by Marinos and Hoek [25]. The discontinuity structure/discontinuity surface condition determined for the GSI was defined as fragmented/weak for the Porsuk formation, blocky-disturbed/weak for the Weathered Bozüyük Granatoid, and multi-blocky/medium for the Bozüyük Granatoid. The average values of the laboratory results given in Table 1 for the rock mass parameter were entered into the rocklab computer software. The rock mass and Hoek-Brown parameters in the numerical analyses were determined (Table 3).

Table 3. Rock-rock mass and Hoek-Brown parameters of T35-GT2 tunnel faces that were numerically analyzed

Features	**Rock Mass Parameters**		
Lithology	**Porsuk Formation**	**Weathered Bozüyük Granitoid**	**Bozüyük Granitoid**
GSI	20	25	45
Average Tunnel Depth (m)	17	30	50
Disturbance Factor	0	0	0,8
Deformation Modulus (E_{mi}-MPa)	539,96	1067,12	2926,32
Mi	6	27	29
Mb	0,345	1,854	1,098
s	0,0001	0,0002	0,0002
a	0,544	0,531	0,508
Cohesion (MPa)	0,039	0,14	0,243
Friction Angle	35,55	52,56	50,99

2.3. Advanced Analysis

Rocscience Phase 2D Version 8.005 [26] software was used for numerical analysis. According to NATM classifications, support elements are suggested in Table 4 and Table 5 based on "KGM, NATM Applied Underground Tunnel Works Technical Specification" [27].

Table 4. Supporting elements for the tunnel sections.

Geological Unit	**Porsuk Formation**	**Decomposed Bozüyük Granitoid**	**Bozüyük Granitoid**
Shotcrete Type and Thickness	C20 25 cm	C20 20 cm	C20 15 cm
Steel Mesh Type and Quantity	Q221x221 2piece	221x221 2 piece	221x221 1 piece
Steel Retaining Type	I 160	I 140	-
Rock Bolt Type and Number	SN 12 piece	SN 9 piece	SN 7 piece

Table 5. Input parameters for tunnel support elements [23].

Features	Shotcrete	Rock bolt	Steel shoring	Wire Mesh
Elasticity modüle, E (GPa)	20	200	200	200
Poisson ratio,	0.20	-	0.35	0.35
Uniaxial compressive strength, (MPa)	20	-	400	500
Residual uniaxial pressure strength, (MPa)	3.5	-	-	-
Tensile strength, (MPa)	3.1	-	500	500
Residual tensile strength, (MPa)	0	-	-	-
Pulling capacity (MN)	-	0.25	-	-
Residual pulling capacity (MN)	-	0.025	-	-
Type	-	28 mm SN bolt	I profile	06.5 mm

Table 6. Tunnel excavation stages for the first zone.

Stage order	Definition of Stage
1	Pre-excavation status
2	Tunnel excavation
3	Placement of steel shoring and shotcrete
4	Placement of Rock Bolts

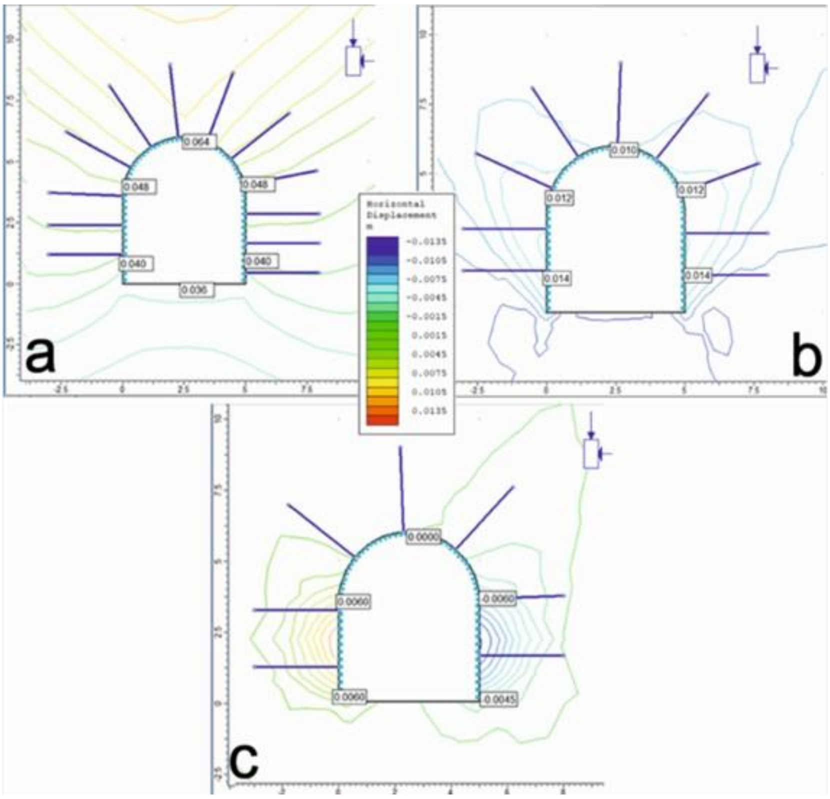

Figure 5. Numerical analysis with the Phase program total displacement amounts (a: Porsuk formation b: weathered Bozüyük Granitoid, c: Bozüyük Granitoid)

Each excavation step needs to be defined after the finite element mesh has been created. The principal stresses, deformation stresses, and surface settlements on the tunnel lining are different at each excavation step. To determine these, each excavation man was evaluated separately, and the steps used in the analysis are given in Table 4. After the tunnel excavation-support stages were defined in the program, the plastic calculation method was used. The generalized Hoek-Brown failure method was preferred since the geological units on the tunnel route show rock behavior.

With the help of this method developed for jointed rock environments, the Hoek-Brown criteria to be used in numerical analyzes are determined from the existing rock material and rock mass parameters [28]. In addition, for the "K" parameter, which is defined as the ratio of horizontal stress to vertical stress in the analyses, the horizontal and vertical stresses are taken as equal (K=1) since the tunnel is close to the surface in the Porsuk Formation unit. The gravity value described in the "Phase user manual 4" is used in the real surface model in other units. After the finite element mesh was created by Phase 2D, each excavation step was defined. The principal stresses, deformation forces, and surface settlements on the tunnel lining are different in each excavation step. Each excavator was evaluated separately to determine these, and the steps used in the analysis are given in Table 6. After the tunnel excavation-support stages were defined in the program, calculations were made using the plastic and Mohr-Coulomb fracture criteria. Fig. 5 was given the total displacement amounts calculated in the numerical analysis results of the Phase 2D program.

3. Measurements During Tunnel Excavation

During tunnel manufacturing, measurements must observe and monitor deformations to control projects' adequacy [29-32]. It includes observation instrumentation, according to Peck [33]. In this case, it can be done in two steps. 1) primary observation and 2) instrumented observation [34]. Preliminary observations; rock mass properties including rock mass classification; Characteristics of discontinuities, faults, and shear zones (it is recommended to adopt qualitative and quantitative definitions proposed by ISRM [35]); instrumented (instrumented) observations include displacements, deformations, pore pressure, etc. around the tunnel and in front of the advancing tunnel face, including structural components used for support. It includes instrumental measurements to measure. Convergence measurements are the most used instrumental measurement methods. It is based on determining and measuring the compatible point with the supporting elements at regular intervals to assess the tunnel's mobility. The geodetic method (accuracy of measurements: ± 1.0 mm) from a remote theodolite station [10].

Convergence measurements in the tunnel along the T35-GT2 tunnel were made by creating a station every 10 meters. Measurements were carried out at 3 points as axis, left, and right foot (Fig. 6). The deformation data obtained by numerical analysis and the deformation data realized in the tunnel are given in Table 7. When the measurement results are evaluated, the numerical analysis and in-tunnel measurement results are parallel in the Porsuk Formation and the weathered Bozüyük Granitoid region.

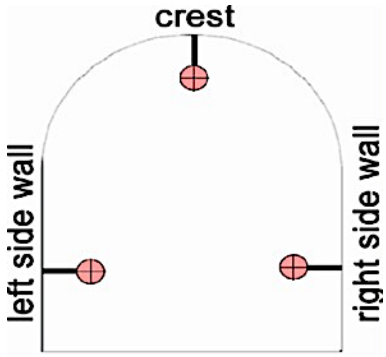

Figure 6. Tunnel deformation measurement points.

It was assessed that the differences in mm's order in the vertical and horizontal deformations were due to the time elapsed between installing the deformation point inside the tunnel and the first reading. The total deformation data's differences are caused by the Phase program, which performs 2-dimensional analysis and 3-dimensional inside tunnel measurements. The Porsuk Formation and the weathered Bozüyük Granitoid were realized as predicted by the region's numerical analysis and in-tunnel measurement results. No problems were encountered in these regions. However, the situation is different in the Bozüyük Granitoid region. In this region, numerical analysis and in-tunnel measurements differ, and in-tunnel sizes are larger in cm.

Table 7. Table of measurements inside the tunnel and numerical analysis (meas. are in mm).

		Numerical Analysis Results			**In Tunnel Measurements**		
	Displacement (mm)	**Axis**	**Left Wall**	**Right Wall**	**Axis**	**Left Wall**	**Right Wall**
Porsuk Formation	Horizontal	0	21	-18	0,7	21,5	-14
	Vertical	64	37	37	61,4	30,7	33,7
	Total	64	40	40	67,58	42,15	38,15
Weathered Bozüyük Granatoid	Horizontal	0	10,5	-10,5	3	24	24
	Vertical	-10	-12	-10	-15	-19	-19
	Total	10	14	14	17	30	26
Bozüyük Granatoid	Horizontal	0	6	-6	0	3	3
	Vertical	-12	-7,5	-7,5	-11	-6	-8,2
	Total	12	9	9	11	6	8

4. Back Analysis

To understand the reason why the deformations in the Bozüyük Granitoid region are high in numerical analysis, the tunnel geological map forms kept at each excavation step during the tunnel construction were examined, with 47 discontinuity data determined in this section of tunnel face, the discontinuity orientations were based on stereographic projection and using Rocscience Dips v.6.008 [36] software. Main discontinuity sets were determined (Figure 7). It is understood from the contour diagram that there is a two-way joint system and a fault zone that was not foreseen during the tunnel design phase. To understand the effect of discontinuity data on deformation, discontinuity sets and fault zone data were added in stages to the analysis made with the parameters and fracture criterion compiled for Bozüyük Granatoid in Chapter 2, and the analyzes were repeated.

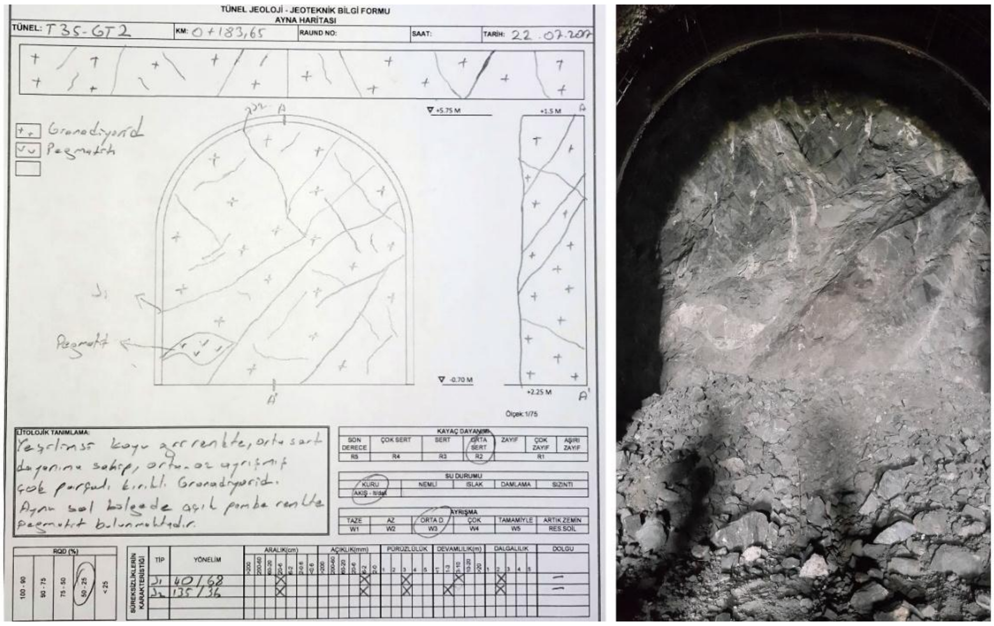

Figure 7. Tunnel face and geological map form of Bozüyük Granitoid region.

In these analyzes; In the Programa Beacher model, 1st discontinuity set has 67/47 crack stop, 7 meters discontinuity continuity, 3 mm quartz filling between cracks, 2nd discontinuity set 140/35 crack stop 3 meters discontinuity continuity and unfilled; For the fault zone, it was positioned in the direction of the tunnel and entered into the program as 68/337 stance, 15 meters continuity, 5 mm quartz filled (Figure 8 and 9). The analysis results and the results of the deformations encountered in the tunnel are summarized in Table 8.

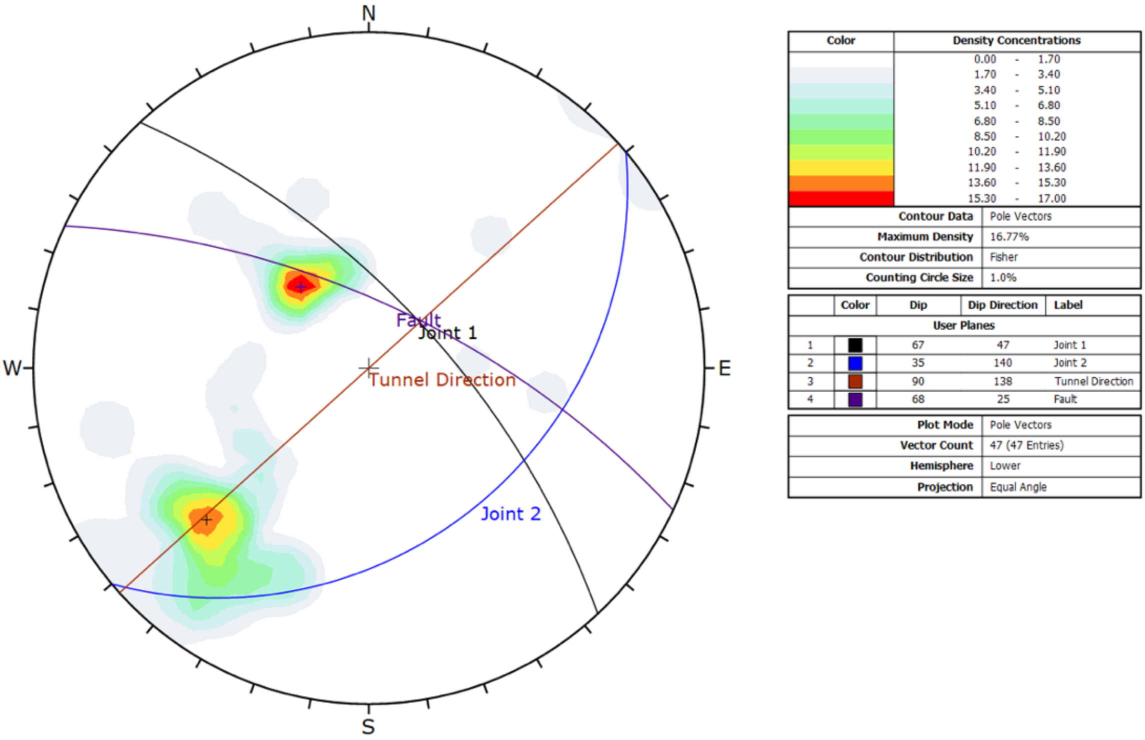

Figure 8. Stereographic diagram of the main discontinuity sets.

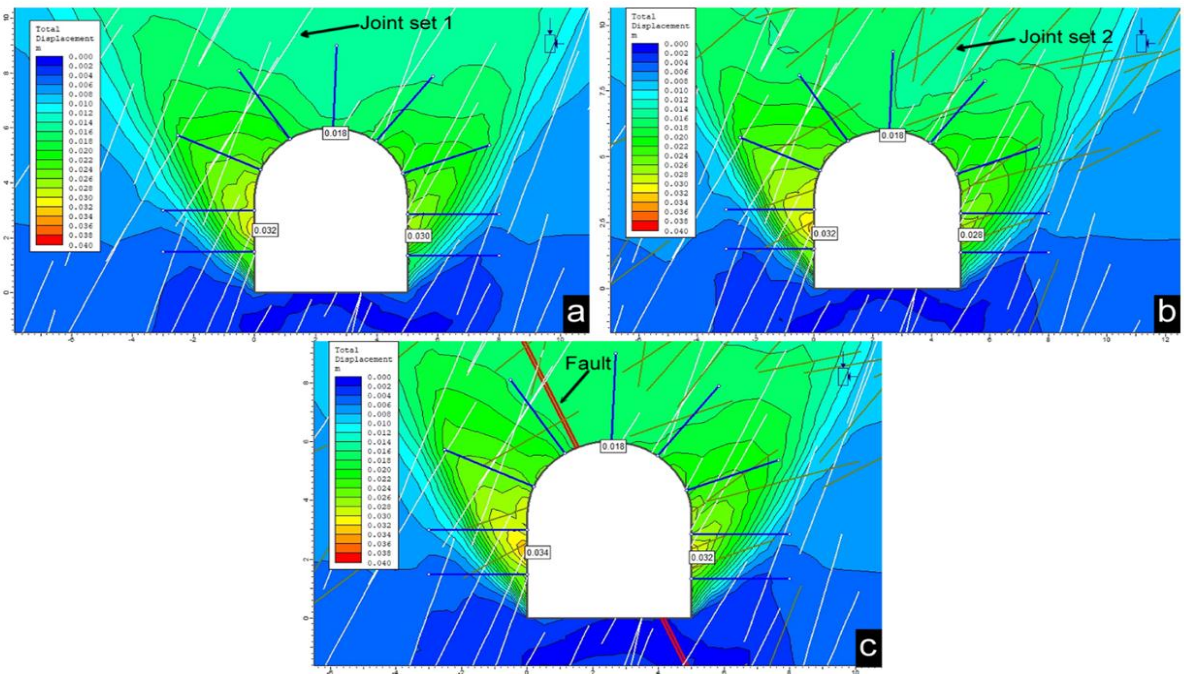

Figure 9. Bozüyük Granitoid region Deformation data of the third region evaluated by numerical analysis (a: Analysis with 1st discontinuity set added, b: Analysis with 1st and 2nd discontinuity set added, c: Fault, 1st and 2nd discontinuity set added analysis)

Table 8. Numerical analysis and in-tunnel measurement results when directional discontinuity is added (mm)

	Analysis results with 1 discontinuity set added			**Analysis results with 2 discontinuity set added**			**Analysis results with 2 discontinuity set and fault added**			**In Tunnel Measurements**		
Displacement (mm)	Axis	Left Wall	Right Wall	Axis	Left Wall	Right Wall	Axis	Left Wall	Right Wall	Axis	Left Wall	Right Wall
Horizontal	0	30	-24	3	27	-24	0	30	27	3	24	24
Vertical	-18	-16	-14	-18	-16	-14	-18	-18	-14	-15	-19	-19
Total	18	32	30	18	32	28	18	34	32	17	30	26

5. Conclusions

Computer-based modeling has frequently found its way into the field of engineering in recent years. The predictability of excavation supports in tunnel applications dominated by different parameters ensures that unexpected conditions are avoided during manufacturing. For this purpose, unit volume weight, poisson’ s ratio, elasticity modulus, cohesion, and internal friction angle values are defined for the geological units encountered along the tunnel route. In this study, the performance of the excavation-support system envisaged in the T35-GT2 tunnel, which has not been studied before, is located on the border of the old and young units. It opened in different geological conditions (in moderate-weak and very weak rocks) compared to the other safety tunnels, is focused on the performance of the excavation-support system. For this purpose, the geological model of the tunnel was created. The tunnel is divided into three different sections by evaluating the geological and geotechnical conditions encountered in the tunnel route. A geological-geotechnical model was created for each section and analyzes were made according to these models. The model created was transferred to the Phase 2D V.8 package program for numerical analysis. Phase program is a finite element program developed in Geotechnical Engineering for deformation and stability analysis of underground structures, cuts, fillings, deep foundations, and piles.

The geological and geotechnical data of Tunnel 35 Safety Tunnel 2, the study’s subject, was taken from previous studies and modeled in the program. The situations are also examined during the excavation support stages by introducing the program's selected supports and excavation-support stages. In the analyzes, the distribution of effective principal stresses, the regional distribution of vertical, horizontal and total deformations, and the forces acting on the braces and cross-section investigations were made. The obtained analysis results and the deformation data obtained during tunnel manufacturing studies were compared. The following conclusions can be drawn from this study:

- It has been observed that rock conditions with no or little discontinuity effect can be predicted by numerical analysis. However, in cases where both drilling and surface observations cannot determine the discontinuities. It has been observed that there are problems in predicting the tunnel with numerical analysis due to missing data.
- When the discontinuity sets and fault data obtained during the tunnel excavation in steps are added to the analyzes, it is seen that the hard-filled and limited continuity has a limited effect on the displacements in the analysis, but when all data are entered together, it gives almost the same results as the deformation data in the tunnel.
- This situation showed that discontinuity data should be collected as much as possible for cost-effective tunnel design in small-diameter tunnels at the project stage. The support system should be corrected, when necessary, by the back analysis method during the manufacturing works.

Authors' Contributions

This study includes the results of ŞU's master thesis. ŞU designed the model of the project in collaboration with NU, and ŞU ran the computer program and obtained the results of models in collaboration with EP. ŞU, NU, and EP evaluated the results and wrote the article, and NU wrote an English version. All authors have read and approved the final version of the manuscript.

Competing Interests

The authors declare that they have no competing interests.

Refereneces

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