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Tunnel Portal Design in Landslide and Active Seismic Geotechnical Environment (T1 Tunnel, Türkiye)

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Abstract: Portal design in extremely weak rock conditions is one of the most challenging tasks in tunnel construction. Because deformations experienced after the start of tunnel excavation, failures in the support system and surface subsidence are generally related to portal design. Therefore, the most suitable location is preferred for portal location. However, in structures such as High Speed Trains, which have various route design restrictions, sometimes the portal location cannot be chosen, a mandatory portal location is determined. In such cases, the most suitable portal design must be developed considering the adverse in-situ conditions. This study focuses on the T1 tunnel entrance portal located approximately 120 m away from the North Anatolian Fault (NAF), one of the most important active tectonic environments in the world. The T1 Tunnel Portal, located 1.5 km South East of Sapanca Station in the Ankara-Istanbul High Speed Train Project, had to be designed within the intercalation of loosely gravel, sandy gravel, sand and silt and the landslide formed in this unit. For the purpose of portal design, landslide geometry was determined with surface observations, drillings and in-situ experiments, and soil parameters were determined by back analysis in the 2D limit equilibrium method. In order to provide landslide rehabilitation and tunnel stability, an approach based on the combined use of bored piles in different patterns and cut-and-cover tunnel structures were designed. The design was controlled using 2D and 3D finite element methods and the most appropriate solution was obtained. As a result, T1 Tunnel Portal construction was completed without any problems in July 2023.

Keywords: Tunnel portal design; Landslide; North Anatolian fault; Bored pile; Numerical analysis; Back analysis

1. Introduction

Due to the design constraints of high-standard railways, tunnels are frequently used (Poşluk and Korkanç, 2018; Aygar and Gökçeoğlu, 2021; Poşluk, 2022; Poşluk et al., 2025). In tunnel construction, a tunnel portal structure is built for reasons such as optimizing the tunnel length, reducing aerodynamic effects at the tunnel entrance, and ensuring tunnel excavation. In regions where portal structures are located, the overburden thickness is generally low, weathering is high, highly jointed and weak rock masses exist (Fei et al., 2012). Construction of a portal in such environments can disrupt the balance and stability of the original slope and cause landslides or failures. In regions where seismic activity is high, tunnel portal stability under dynamic conditions is essential (Wang, 2023). Seismic damage studies of tunnels under multiple strong earthquakes show that tunnel portals are the most vulnerable areas to earthquake damage (Yu et al., 2013), and portal section supports are the weakest points (Dowding and Rozan, 1978). The Bolu Mountain highway tunnel portal was damaged in the Kaynaşlı, Turkey (7.2) earthquake on November 12, 1999. Similarly, in the study conducted in fifty-seven tunnels in the seismic region after the 1999 Chichi earthquake, it was stated that most of the tunnel portal damage was caused by lining damage and slope collapse (Wang et al., 2021). During the 2004 Niigata earthquake, a landslide occurred in the weak rock at the Kizawa tunnel portal, resulting in serious cracks in the tunnel portal (Asakura et al., 2000, Konagai et al., 2009). In the February 6, 2023 Kahramanmaras earthquakes, cracks occurred in the portal of the Erkenek highway tunnel (Apostolaki et al., 2024). A

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landslide occurred in the Aşık Mahsuni Şerif tunnel portal in Kahramanmaraş, but this landslide did not affect transportation. Following the same earthquake, the T3 and T7 conventional railway tunnel portals were damaged and a landslide occurred in the T3 tunnel portal (Karahan et al. 2025). Therefore, it is imperative that the factors affecting the portal be well studied and examined under dynamic loads during tunnel design. If this is not performed, the tunnel may be damaged and transportation networks may be closed. This is the last thing you want during a disaster. Consequently, the present study focuses on the T1 Tunnel Portal design, which is constructed within an active landslide and 150 m away from the Dokurcun active fault segment of the North Anatolian Fault Zone (NAF) (Fig. 1a), one of the most active tectonic environments throughout the world. The study is an interesting case study in terms of presenting new approaches in terms of portal design that includes both earthquake and landslide effects.

2. T1 Tunnel Setting

T1 Tunnel is located on the 530 km long Ankara-Istanbul High Speed Railway Project, 1.5 km east of Sapanca station (Fig. 1b). The T1 tunnel in the north-western part of Türkiye lies between km: 124 + 660–127 + 548 of the Ankara-Istanbul high-speed train project, with a total length of 2888 m (Aygar et al., 2023), and it is a 12.5 m wide and 8.1 m high double-track single-tube high-speed railway tunnel (Fig. 2). Approximately 60 m of the Entrance Portal area of the tunnel (km: 124+600 to 124+660) is within the active landslide (Fig. 1b).

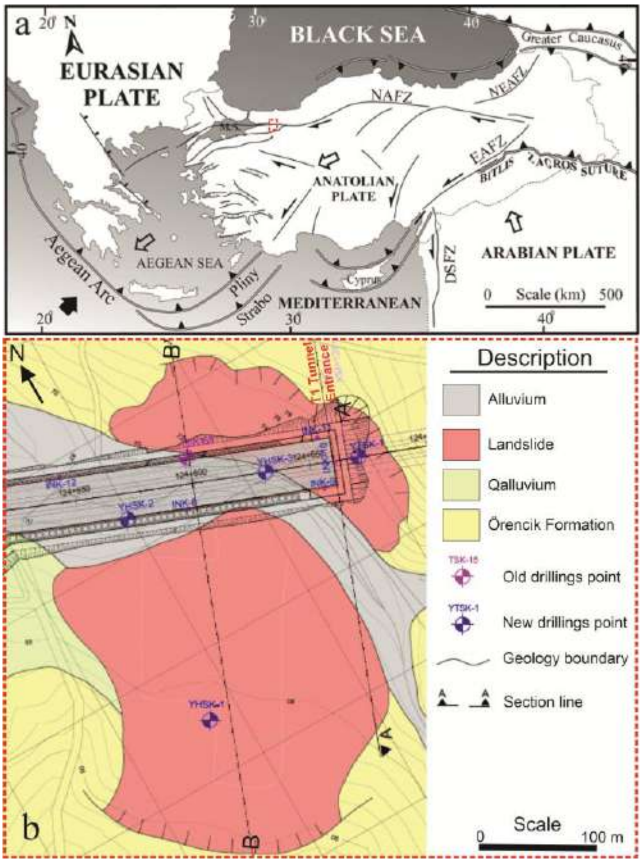

Fig. 1. (a) Tectonic outline of Turkey and eastern Mediterranean area. MS: Marmara Sea. NAFZ: North Anatolian Fault Zone. EAFZ: East Anatolian Fault Zone. DSFZ: Dead Sea Fault Zone. NEAFZ: North East Anatolian Fault Zone (Gürbüz and Güler, 2008) (b) Geological map of the study area (Fugro-Sial, 2020).

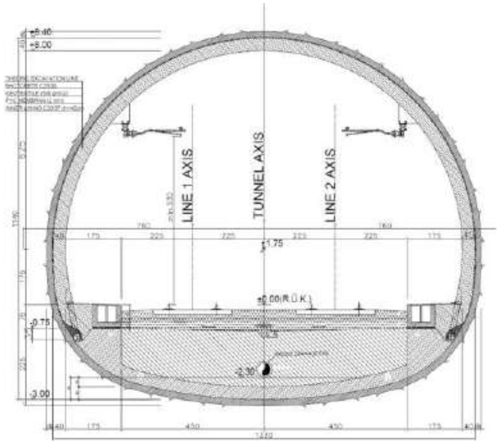

Fig. 2. Typical cross section of the T1 tunnel (units are in cm).

2.1. Geological setting

The Tunnel 1 entrance portal passes through terrestrial clastic sediment units. These units, called the Örencik Formation, are Pliocene-Quaternary in age (Aydın et al., 1987). In the tunnel portal, the units are beige, poorly consolidated, completely disintegrated and crushed claystone, sandstone units are observed to be intercalated due to atmospheric conditions and tectonic movements (Fig. 3a). Towards the T1 Tunnel route, where the overburden thickness increases, the gray-colored, medium-dense to very dense clayey sandstone, sandstone, fine conglomerate intercalation units are completely disintegrated and extremely weak (Fig. 3b).

There is an alluvial plain area starting from the region where the Tunnel 1 Entrance Portal is located and reaching up to Lake Sapanca (Koba, 2017). According to the MTA (2025) study, there is an active (> 2mm/year) landslide on this alluvial plain area, moved towards the NW with a width of 55 m and a length of around 230 m (MTA, 2025). The tunnel base is approximately 10 m below this alluvial plain. Therefore, the tunnel and this section remain within the landslide.

Fig. 3. (a) T1 Tunnel entrance general view, (b) gravel level general view.

2.2. Seismicity

The region where the T1 Tunnel Portal is located is within the North Anatolian Fault Zone (NAFZ). The NAFZ is one of the best known strike-slip faults in the world because of its remarkable seismic activity, extremely well-developed surface expression and importance from the tectonics of the eastern Mediterranean region (Ketin, 1968, 1969; Ambraseys, 1969; McKenzie, 1972; Bozkurt, 2001; Gürbüz and Gürer, 2008; Fig. 1a). This fault zone is a 1600 km-long, dextral strike-slip active transform fault running through northern Turkey in an E-W direction.

Ikeda et al. (1989a, 1989b) have presented some lines of evidence indicating that the NAFZ branches westward into two active fault zones from 30°E: the northern branch called the İzmit-Sapanca fault zone (Ikeda, 1988), and the southern branch called the Iznik-Mekece fault (Sipahioglu and Matsuda, 1986). These branch faults are synthetic faults, being developed at a low angle to the master fault, mainly in the contractional quadrant, but occasionally in the dilational quadrant (Kim and Sanderson, 2006; Fig 3a). These faults have produced devastating earthquakes in recent history. The largest of these earthquakes are the 17.08.1999 Marmara Earthquake (7.4), 12.11.1999 Düzce Earthquake (7.2) and 26.05.1957 Abant (7.1) Earthquake. As a result of these earthquakes, the region where the T1 Tunnel portal is located is in a region affected by very high earthquake accelerations, and according to the Turkish Earthquake Code (2018), the earthquake accelerations affecting the Portal are given in Table 1.

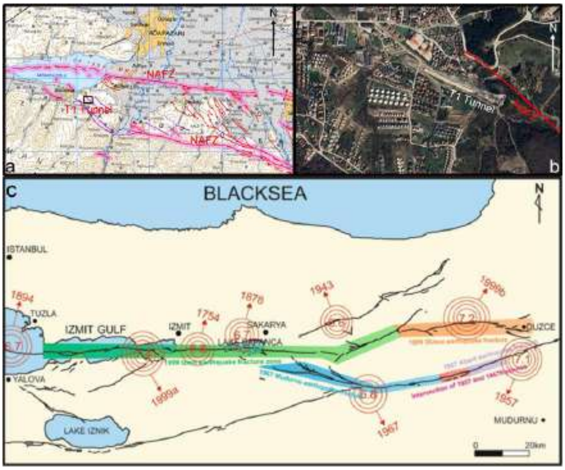

Fig. 4. Active faults around T1 Tunnel (a: Active fault map (Emre et al., 2011), b: Active fault satellite image of the tunnel portal area, (MTA, 2025), c: Fault map showing the location, magnitude and rupture zones of historical earthquakes around Sapanca Lake (Emre et al., 2013).

Table 1. Earthquake accelerations affecting the T1 Tunnel Portal (AFAD, 2025).

	PGA (g)	PGV (cm/s)	S_S	S_1
DD1	1,147	94,583	2,921	0,837
DD2	0,687	56,392	1,687	0,464
DD3	0,296	17,663	0,681	0,164
DD4	0,156	8,434	0,355	0,081

DD1: spectral magnitudes have a 2% probability of being exceeded in 50 years and the corresponding recurrence period is 2475 years; DD2: spectral magnitudes have a 10% probability of being exceeded in 50 years and the corresponding recurrence period is 475 years; DD3: spectral magnitudes have a 50% probability of being exceeded in 50 years and the corresponding recurrence period is 72 years; DD4: spectral magnitudes have a 68% probability of being exceeded in 50 years (50% probability of being exceeded in 30 years) and the corresponding recurrence period is 43 years; PGA: Peak ground acceleration; PGV: Peak ground velocity; SS: spectral acceleration coefficient for short period; S1: spectral acceleration coefficient for 1.0 s period.

3. Engineering Geology

A series of engineering geology studies were performed starting from field observations for design purposes in T1 Tunnel Portal and its close surroundings. In this context, borehole locations were determined on the general geology map prepared by field observations, and laboratory studies were carried out after drilling and in-situ tests. In the last stage, material parameters were determined using the back analysis method for the landslide material employing the determined landslide geometry.

3.1. Borehole investigations

Nine drillings with a total length of 645 m were performed in the T1 Tunnel portal and its vicinity (Fig. 1b). The results obtained from the drillings showed that the groundwater level varied between 2.2 m and 8 m. Of these drillings, YTSK-1 and YHSK-3 were applied in order to determine the landslide failure surface depth. In the YTSK-1 drilling, landslide material is observed up to 14 m from the surface (Fig. 5a and Fig. 6). Then, Örencik Formation units (gravel clay, sand, silty clay) were cut. In the YHSK-3 drilling, on the surface, silty gravel-block sized alluvium with low clay content was passed up to 5 m, then silty clay (Tplö-2) up to 10 m, and landslide material was encountered 16.5 m (Fig. 5b). Starting from this depth, Örencik Formation (gravel clay, sand, silty clay) units were cut in the drilling.

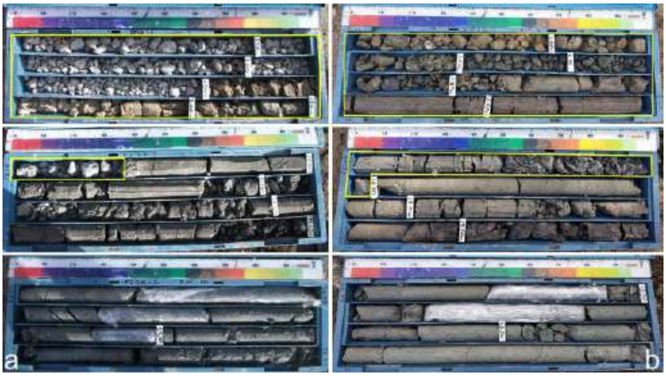

Fig. 5. Photographs of core boxes from the drillings at the T1 Tunnel Portal entrance (a: YTSK-1; b: YHSK-3 drillings, the area within the yellow lines shows the landslide material; Fugro-Sial, 2020).

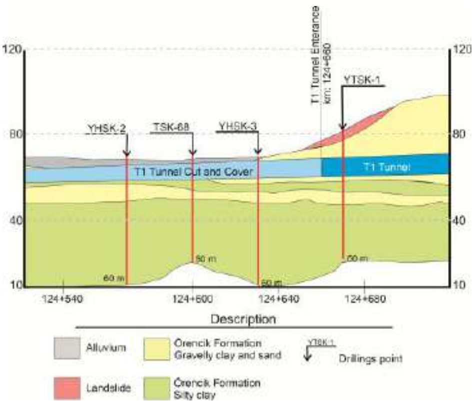

Fig. 6. Geological cross-section of the T1 Tunnel and T1 Tunnel Cut and Cover (modified after Fugro-Sial, 2020).

3.2. Laboratory tests

In the 9 drillings carried out in the T1 Entrance portal, in addition to landslide material, alluvium, gravelly clay and sand, clayey sand and silty clay units were observed. The results of the experiments carried out on the specimens taken from these units are summarized in Table 2. Accordingly, although the units were defined differently, the shear strength parameters were obtained quite close.

Table 2. Material parameters obtained from laboratory tests (Fugro-Sial, 2020).

Description	g (kN/m^3)	c' (kPa)*	♦ (°)
Alluvium	20.5	1	27
Gravelly clay and sand	21.1	1	30
Clayey sand	20	1	28
Silty clay	21.9	1	26

*The value c' is a mandatory value entered into the program.

3.3. Landslide model and back analyses

In order to determine the T1 Tunnel entrance portal landslide material parameters, first, Km: 124+600 (Fig. 1, B-B' section) was selected as the critical slope. Using the drillings performed in the region, 6 different unit boundaries were determined and the possible landslide model and slope geometry were determined (Fig. 7). In this slide model, the back analysis method was used for the parameter determination of the landslide material. The back analysis method covers the process of determining the conditions of a slope at the moment of movement (Ün and Yıldız, 2021, Poşluk et al., 2025). When a landslide occurs, it is assumed that the safety factor (FS) in the slope is equal to or below one. Therefore, the slope model at the moment of movement of a slope can be estimated in a way close to reality (Poşluk et al., 2025). The ground parameters obtained as a result of the calculations are the weighted average shear strength parameters on the sliding surface and the c: cohesion, ϕ: internal friction angle data pairs that provide the FS=1 condition are determined by trial and error (Ün and Yıldız, 2021).

T1 Tunnel portal were analyzed using the Plaxis V10 computer program using the Finite Element Method using the back analysis method. According to the analysis results, the shear strength parameters of the failure surface were determined as c'=1 kPa; ϕ =8.50° and as a result of this analysis, the factor of safety was calculated as 0.99 (Fig. 8).

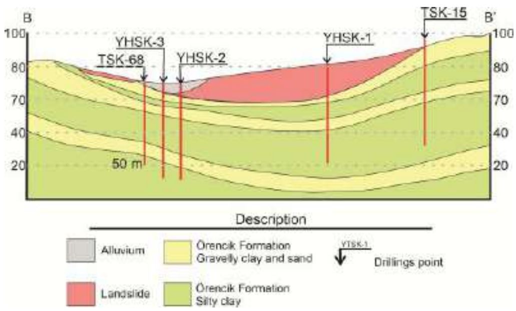

Fig. 7. Landslide model for the tunnel portal (section B-B', modified from Fugro-Sial, 2020).

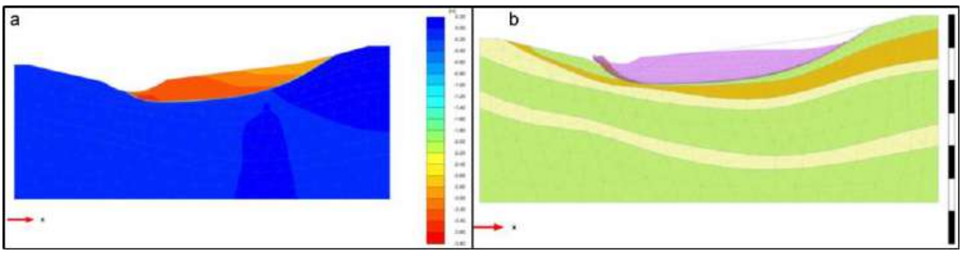

Fig. 8. Back analysis results for T1 Tunnel portal km: 124+600 (a: landslide model in the first case, b: analysis results in the last (current) sliding case; Fugro-Sial, 2020).

4. Slope Stability Analyses

The stability analyses of the T1 Tunnel were carried out in two stages. In the first stage, the required resistance force to ensure stability in the landslide model (Km: 124+600) was found, then the support model was created and the support model was searched using 2 and 3-dimensional finite analysis methods. The factor of safety for the stability of the slope should always be greater than "1" and should be at least "1.3" in short term and at least "1.5" in long-term stabilities (Poşluk et al., 2018). Therefore, in order to produce the optimum engineering solution, a support model was created that first included short-term conditions with bored piles and then long-term conditions with an cut-and-cover structure (Fig. 9). In order to create a temporary structure in a non-earthquake situation, the required resistance structure for a factor of safety of 1.3 was investigated. In this case, the required resultant resistance force was calculated as 1809 kN/m (Fig. 10).

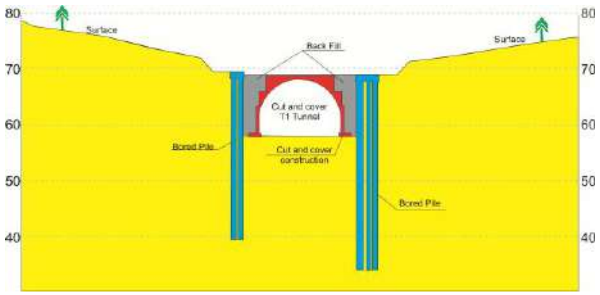

Fig. 9. Portal solution proposed for the T1 Tunnel portal (Fugro-Sial, 2020).

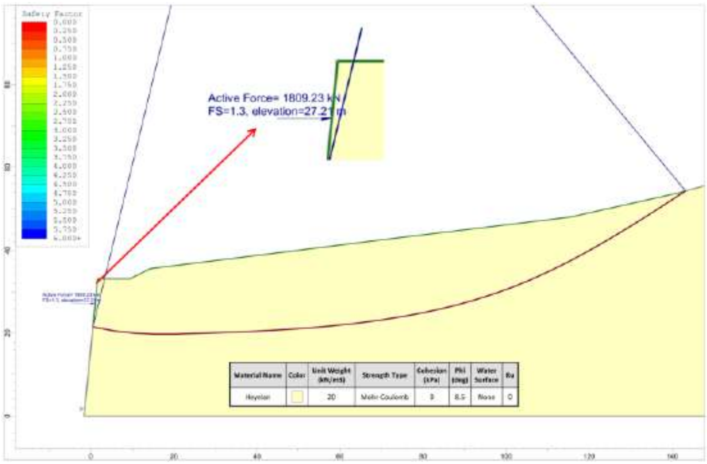

Fig. 10. Required bearing force determined by short-term slope analysis (Fugro-SIAL, 2020).

4.1. Pile retaining structure analysis

In the analyses performed for the safe construction of the cut and cover structure, the soil response was represented by spring coefficients. A vertical spring coefficient of k=200,000 kN/m3 was defined at the pile base. The lateral bearing coefficient was taken from the elasticity module as kn=19,000 kN/m3 for a 1.50 m pile spacing, and k»=29,000 kN/m3 for a 1.40 m pile spacing. The pile system was modeled in 3D in order not to overlook the effects that the geometric differences in plan and profile would create on the 3rd dimension. Plaxis 3D software, which allows analysis with the finite element method, was used in the analyses.

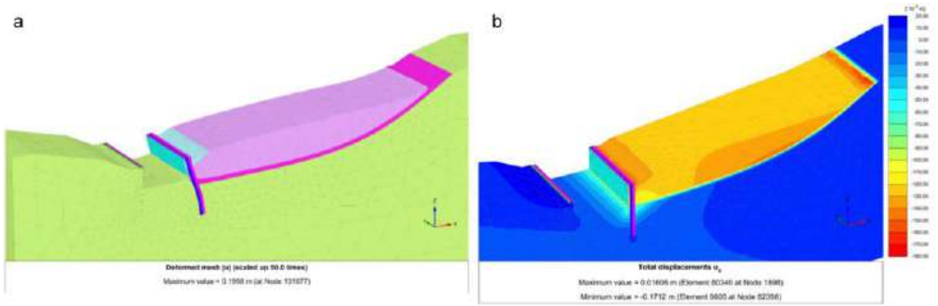

Fig. 11. 3D numerical analysis results for the T1 Tunnel portal landslide support model (a: model, b: analysis result, Fugro-Sial, 2020).

4.2. Analysis for Cut and cover structure

In the bored pile support system proposed in the T1 Tunnel entrance portal section, after the completion of the piles, cut-and-cover structure analyses were carried out in order to ensure seismic and long-term portal stability. Analyses were carried out using the previous material parameters in the critical sections of Km: 124+600 using 2D Plaxis V10 finite element software. For this purpose, excavation and support were divided into 8 stages, piles were placed in the first 3 stages, excavation was made for cut-and-cover in the 4th and 5th stages, cut-and-cover structure was constructed in the 6th stage, 2 m fill was performed on the cut-and-cover structure in the 7th stage and earthquake acceleration according to the DD2 condition (Table 1) was added to the analyses in the 8th stage. In the 7th stage, the factor of safety was determined as 1.56 and 8th stage 1.12 in the seismic (DD2) condition. Construction works started in 2021 and were completed in June 2023 (Fig. 12). To monitoring movement in the cut-and-cover structure during and after construction, seven inclonometer pipes were installed in the bored piles. Three convergence measurement points were determined at the midpoint of every 12 m of slab within the reinforced concrete cut-and-cover structure. Measurements were taken over 13 months, including the rainy season. According to the measurement results, the highest inclinometer readings were 0.7 mm and the highest convergence readings were 3 mm. These measurement results are negligible.

Fig. 12. T1 Tunnel portal construction stages (a: completion of bored pile construction, b: cut-and - cover construction and backfilling stage, c: T1 Tunnel portal completed status).

5. Conclusions

As a result of the technical standards and geometric restrictions required in high standard railways, tunnels sometimes that must be constructed in shallow and weak rocks/soils may inevitably need to be passed. In tunnels in such regions, the most challenging parts are the tunnel portal regions. Because the problems in these regions directly affect the tunnel excavation and cause cost and time loss. Therefore, the problems in the tunnel portal section should be solved before starting the tunnel excavation. The T1 Tunnel entrance portal in the Ankara-Istanbul High Speed Train Project, which is the subject of this study, is one of the best examples of portal structures constructed under difficult conditions. The T1 Tunnel portal is located in gravelly clay, sand, clayey sand, silty clay units and also passes through an active landslide. In addition to these, it is 150 m away from the Dokurcun active fault segment, which is one of the segments of the NAF. With these features, it requires quite challenging engineering solutions. In order to provide landslide rehabilitation and create a tunnel portal, the landslide geometry was tried to be understood with field observations and drillings, and then the material parameters were determined using in-situ tests, laboratory tests and back analysis method. The planned bearing and cut-and-cover structure was analyzed with 3D and 2D numerical analysis methods, considering the earthquake conditions, and the construction was completed in July 2023. It was concluded that the structure, which was evaluated with the measurements made in the structure, showed a successful performance. It was concluded that the research and application procedures proposed within the scope of the study are guiding for similar structures to be built in the future.

Acknowledgements

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