Assessment of collapse mechanism of a High Speed Railway Tunnel (T341 Tunnel, Turkey)

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Abstract. Excavation and implementation of tunnel support system of T341 tunnel of Ankara-Sivas High Speed Train Project were completed recently. Throughout the tunnel excavation, serious stability problems occurred both in the entrance portal section and tunnel. The purposes of this study are to explain the failure mechanism and to propose a suitable support system for the section between Km: 341 + 040 - 341 + 114. Tunnel works were interrupted after the collapse, which occurred in a section of approximately 74 m between Km: 341 + 040 - 341 + 114. As a result of the collapse in the tunnel, local settlements emerged on the surface and it was observed that the effects of the collapse on the surface, as well. To surpass the collapsed section, extra reinforcements were performed by grouting taking place both at the surface and inside the tunnel. Afterwards, tunnel excavation was completed in relatively short stages by applying double umbrella system and rigid support system. Consequently, the causes of the failure, excavation and support system design and results of the numerical analyses are discussed.

Keywords: Tunnel, High-Speed Railway, T341 Tunnel, Collapse, Grouting

1. Introduction
The T341 tunnel of Ankara–Sivas High-Speed Railway Project of Turkey is located between Km: 340 + 860 (entrance portal) - Km: 342 + 080 (exit portal), was completed successfully. The length of the tunnel is 1220 m. Figure 1 shows the location of the tunnel, and some Google Earth views of the tunnel portal locations are given in figure 2. In March 2020, after the tunnel excavation and supports were completed, inner lining concrete was started. However, sudden deformations occurred between Km: 341 + 040 - 341 + 114, and a sudden failure occurred in this part of the tunnel (figure 3). After this stage, the tunnel works had to be suspended. The main purpose of the present study is to explain the failure mechanism and to propose a new design system. After the ring is closed and the deformations are completed, a failure in a tunnel is not expected in general. Therefore, investigation of this unusual situation is an interesting case for tunneling. For the purpose of the study, the previous documents including geological and geotechnical investigations, projects, construction stages and deformation measurements were examined, and the field observations were performed.

Collapse problems in tunnels are generally caused by insufficient supports during the tunnel excavation (Aygar and Gokceoglu, 2019a, b). In these cases, material inflows occur into the tunnel from face. This situation causes a gap in the face section in front of the tunnel (Aygar and Gokceoglu 2020a, b). If the cover height is low, some sinkholes can be observed at the surface.
Figure 1. Location map of the study area

Figure 2. Google earth views of the portals

Figure 3. Failure zone in the tunnel
Another collapsed situation consists of the inability of the supports to bear the loads in the long term where the excavation has been completed and external supports have been made. This is usually due to the fact that support systems are not constructed correctly (Aygar, 2020). Also, the squeezing conditions affect the supports negatively (Aygar and Gokceoglu, 2019b). Moreover, it is known that unexpected earthquake loads also negatively affect the supports in areas where deformations continue (Aygar, 2007).

2. Geological Characteristics of the Tunnel Route
The T341 tunnel was excavated mainly in Pazarcık volcanics (Tep), Tokuş formation Banaz member (Ttb) and Sarkavak member (Pzkas). The Banaz member (Ttb) consists of gray - bluish gray and brown colored, medium hard - hard, medium strength, low strength, slightly - moderately weathered and partly weathered mudstone unit. The 5.50 meters thick upper levels of this unit are completely weathered and are of sandy clay. The Sarkavak member (Pzkas), which is commonly observed along the tunnel route, consists of a gray-brownish gray colored, hard, partly low-medium hard, moderate strength, partly weak-strength, slightly-moderately weathered and partly weathered marble unit. The contact of these units observed along the tunnel route is tectonic. In sections close to tectonic lineaments, rock units display a chaotic weathering and strength pattern. In addition, sudden surface/groundwater discharges were observed in these fault zones (Yüksel Proje, 2011).

3. Evaluation of the Collapsed Zone and Solutions
After completing excavation and support operations in the T341, as a result of unexpected severe deformation, a collapse occurred inside the tunnel. This collapse not only affected the outer lining but also the inner lining. In addition, cracks and fissures occurred on the surface. First of all, reinforcement of the collapse zone by grouting from the surface and the face, and then rigid excavation with self-drill bolts were considered as the most appropriate option.

The excavation of the collapse was completed in 3 main stages:
- First, the inside of the collapse was reinforced by grouting from the surface into the collapse.
- Afterwards, reinforcement of the collapse with the grouting was performed from the collapse face.
- The final stage was planned as tunnel excavation of the reinforced collapse with self-drill bolts.

3.1. Determination of Tunnel Support Systems
2D numerical analyzes were carried out to determine tunnel support systems. Phase2dv8.0 program was used in the numerical analysis. In the analyzes, first, necessary analysis was performed to determine the parameters of the collapse section, and then new support systems were performed considering these parameters. The analyzes were performed in a total of 20 stages (table 1).

3.2. Determination of the ground parameters
In order to determine the parameters of the disturbed section, analyzes were made with different cohesion, internal friction angle and modulus of deformation values, and it was determined for the ground parameters of the collapse zone.

As shown in figure 4, deformations up to 70 cm occur in the upper half of the analysis performed. These deformations occurred when the support class was C3, and they reflect the ground conditions. The parameters obtained from the back analyzes are summarized in table 2, and the parameters for the improved section are given in table 3.

3.3. Evaluation of the Analysis Results
Numerical analysis results are given in figures 5-7. As can be seen from the analysis, as a result of the reinforcement, a displacement of 1 cm around the tunnel occurs. There is a swelling up to 8 cm at the invert only, and it remains within the deformation tolerance at this value. The safety factors around the tunnel are above 1 around the tunnel, and increase as the distance to the tunnel increases. In addition, when looking at the collapse areas around the tunnel, no failure occurs in the grouted zone. When the forces on the bolts are examined, it is seen that the bolts are under the carrying capacity. The axial forces on the bolts are lower than 121 kN.
### Table 1. Modelling stages for Phae2d

| Stage | Phase                                                                 |
|-------|------------------------------------------------------------------------|
| 1     | Initial stress conditions                                              |
| 2     | Installation of the umbrellas                                          |
| 3     | Top heading excavation                                                 |
| 4     | Installation of the support systems                                    |
| 5     | Occurring the collapse                                                 |
| 6     | Grouting of the collapsed zone                                         |
| 7     | Excavation of the half section in top heading                          |
| 8     | Installation of the support systems and installation of the intermediate invert |
| 9     | Excavation of the other half section in top heading                    |
| 10    | Installation of the support systems and installation of the temporary invert |
| 11    | Left bench excavation                                                  |
| 12    | Installation of the support system                                     |
| 13    | Right bench excavation                                                 |
| 14    | Installation of the support system                                     |
| 15    | Excavation left invert section                                         |
| 16    | Installation of the supports and filling concrete                      |
| 17    | Excavation right invert section                                        |
| 18    | Installation of the supports and filling concrete                      |
| 19    | Reset all displacements                                                |
| 20    | Removing the outer support systems, installation of the inner lining and seismic loading |

**Figure 4.** Deformation after top heading excavation and collapsed zone
Table 2. Geotechnical parameters (Fugro Sial, 2020)

| Cohesion (kPa) | Internal friction angle (°) | Modulus of Deformation (MPa) |
|----------------|-----------------------------|-----------------------------|
| 20             | 20                          | 100                         |

Table 3. Geotechnical parameters after improvement of the ground

| Cohesion (kPa) | Internal friction angle (°) | Modulus of Deformation (MPa) |
|----------------|-----------------------------|-----------------------------|
| 500            | 0                           | 1000                        |

Figure 5. Total displacements

Figure 6. Strength factor around the tunnels

4. Ground Improvement for Collapsed Zone
First, the topography of the collapsed area was leveled, and a platform was created for the injection process on the surface, then 1.5x1.5 meters of grids were considered for the injection holes at the beginning with a cement-mixed injection at the rate of 1/1 (w/c), and then, this ratio was increased to 5/7. Whenever this process is completed, the collapsed area was completely improved by grouting starting from the collapsed tunnel face. Figure 8 shows the injection pattern from the surface, and figure 9 shows the injection pattern from the tunnel face.
Figure 7. Yielding zone around the tunnel

Figure 8. Consolidation grouting for collapsed area (Fugro Sial, 2020)

Figure 9. Face injection in the collapsed area (Fugro Sial, 2020)
4.1. Excavation in the collapsed zone details

After the injection procedure described above is completed, the collapsed zone excavation was started. The following order was considered for the collapse excavation.

1) First, the 1st floor self-drilling pipes of 3.5” diameter and 9 m length at 30 cm intervals were driven at an angle of approximately 8 degrees along the upper half of the tunnel as shown in figures 10 and 11. After the 1st layer umbrella were applied, the second layer umbrella were installed at an angle of 15-20 degrees.

2) Self-drilling bolts were applied along the tunnel perimeter was not only be used for bearing the ground, but also for the injection of the collapse area. Therefore, the injection was performed without any restrictions during the process.

3) The excavation of the collapsed zone was performed in excavation stage of 0.75 m. After each excavation stage, the next excavation was not be carried out until the support systems were completed.

![Figure 10. Support system details for collapsed zone (a)](image)

![Figure 11. Support system details for collapsed zone (b)](image)
4) The support systems (figures 10 and 11) are:
- Tunnel excavation (Excavation stage is 0.75 m),
- Lining the surface and face with shotcrete including 7 cm fibers,
- Installation of 1st layer mesh steel (Q589/443) and lattice girder
- Completing the shotcrete to 25 cm (C30/37)
- Placement of Q589/443 type mesh steel on the second level,
- Completing the shotcrete to 30 cm (C30/37),
- Installation of self-drilling bolts and injecting.
- 3.5 "diameter 9 m long self-drilling bolt system (Double Layer)
- When reaching 12 m in invert excavation, invert concrete was placed.

5. Conclusion and Recommendations
An interesting failure in the T431 tunnel between Km: 341 + 040 - 341 + 114 occurred after the ring was closed. As soon as the collapse occurred, the ground improvement was provided by grouting, from the surface and from the tunnel face. Subsequently, the excavation and support operations of the double-layer umbrella on the tunnel face were carried out successfully in a short time. Consequently, the T341 tunnel was completed successfully, and it was opened to traffic.

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