Evaluation of uncertainties in travertine rock mass for the Antalya (Turkey) Metro tunnel excavation

Mehmet Ozcelik and Merih Can Aydemir

ABSTRACT

The uncertainty in the measurement of rock mass is largely due to the inherently heterogeneous nature of the rock mass itself. A variety of environmental conditions influence the engineering behaviour of the rock mass. Antalya settlement area is located on the travertine deposits. Travertines were affected by domestic and industrial liquid waste, which was injected directly into the travertine plateau through septic holes in Antalya prior to 2000. This situation resulted in poor engineering properties in travertine rocks, such as high deformation and low strength. It can cause issues in travertine foundation excavations. Determining all engineering parameters, ordering their weights and clarifying their uncertainty effects are especially difficult tasks in tunnel excavations. This paper addresses the most important aspects of the Antalya 3rd Stage Rail System tunnel project and examines the rock mass properties of karstic travertines.

1. Introduction

Tunneling and underground excavations are examples of large-scale complex systems engineering that can involve a variety of uncertainties during construction. Tunnelling and underground construction are always associated with inherent risks due to limited knowledge of, and uncertainty about, the existing geological conditions at the site. In particular, when examining the geological conditions of complex areas such as karst development, various safety accidents such as collapses [1] and runoff water [2] can easily be triggered, affecting all stakeholders as well as those not directly involved in the project [3]. Several case studies reported worldwide [4–8] suggest that uncertainties in the geology and complexity of tunnel construction processes often result in construction delays and cost overruns [9–12]. Travertines from Plio-Quaternary are exposed in the vast area around the Antalya region. Travertine is in this area the major subgrade formation. Where the surface rock is travertine, the travertine was submerged in karst terrain exemplified by features such as open, clay-filled voids and dissolved poor rock zones. For several years, wastewater from residential areas and existing industries were connected to septic holes around Antalya for their discharge. Septic holes allow the surface and wastewater of the underlying travertine to penetrate through cracks. This action in effect travertine weathering, which causes uncertainties. The karst features and the weathered environment posed a significant danger to tunnels and cut-out structures and engineers were confronted with a design challenge. The design and construction of tunnels and underground structures in moderately strong and weak travertine formations has created a variety of problems for geotechnical engineers due to the geological, hydrogeological, geophysical and geotechnical uncertainties of travertines. For this purpose, a quantitative, probabilistic approach has been made to use the Q-system (Q), Rock Mass Rating (RMR) and Geological Strength Index (GSI) system for rock mass characterisation. The compressive strength of the travertine supporting the loads of the foundation and the potential for large-scale subsidence and collapse into karst voids beneath the foundations and structures must be considered. Although the 960-metre long excavation of the double tunnel has been completed using The New Austrian Tunnelling Method (NATM), concrete work is ongoing. Isolation work is also carried out in tunnels. Excavation is performed at the West metro station, at a depth of 27 m, where underground tunnels are connected.

2. Material and methods

Antalya is Turkey’s main tourist destination and receives about 30 per cent of the region’s tourists [13]. With 2.3 million residents, it contributes about 3 percent of...
Turkey's GDP, and is one of the fastest-growing cities in the world. The new tram line is expected to carry an additional 25 million passengers per annum, greatly improving urban mobility and helping to reduce congestion in urban traffic. The project of the 3rd Stage Rail System is approximately 24.9 km long with the main line. The project, starting with Kepez Varsak and joining the nostalgic tram line in front of the Training Research Hospital in Muratpasa-Meltem, will have a total of 39 stations, of which 38 are on the surface and 1 underground tunnel station (Figure 1).

2.1. Uncertainty assessment

It is difficult to expect some underground responses to excavation actions due to the complexity and the heterogeneity of the surrounding medium in tunnel and underground construction. Uncertainty is a condition involving incomplete and/or uncertain knowledge that cannot reliably represent the current state, potential outcomes or more than one possible outcome [15]. Due to the presence of various sources of uncertainty, precise determination of the rock mass properties is very difficult. Some common types of uncertainties are spatial, statistical and systemic uncertainties resulting from in-situ and laboratory testing. By using separate methods with different assumptions, the inherent uncertainty of long-term assumptions can be reduced.

2.2. Geological uncertainties

Tunnelling and underground construction are also related to inherent risks due to inadequate awareness of the prevailing geological conditions at the site and other uncertainties [16]. Geological uncertainties are not only about constructing underground structures, but also about affecting construction activities. The preparation of underground openings and the methods of excavation production must be tailored to the requirements of rock material. It is inevitable that before the tunnel is excavated, the geological conditions will not be fully known, and even then errors can be made in estimating the geological behaviour [17]. Complex and poor geological conditions may cause problems in tunnel and underground excavations [18]. The Travertine Plateau is exposed to an area of 630 km² (Figure 2). The soil profile of the project area consists essentially of a travertine unit overlaid with a soil of varying thicknesses. Geological structures of the travertine unit include some potential uncertainties. The mass of the travertine has uncertainties due to the texture mostly caused by karstic dissolution and primary pores formed during the carbonate coating of the plants. It is difficult to characterise the size and distribution of pores in travertine rock. Pore cavities, especially those developed in the form of dissolution cavities, can be partially or completely filled with precipitates. These precipitates can be clay deposits or calcium carbonate precipitation. Thirty-seven boreholes were executed long the route and at the depot

Figure 1. Location map of the metro alignment [14].
site in order to identify the lithological, geotechnical properties, boundaries, extensions, thickness of soil and rock units and to determine the groundwater level.

2.3. Hydrogeological uncertainties

Karst is a dynamic medium of variability over several levels. Water flow routes, from the rock matrix to fractures and karst features, are present across the entire medium. The hydrodynamic role of these waterways remains poorly understood [20] and regulation of karst water flows remains a significant issue. Karst hydro systems have a high degree of permeability since a large quantity of water flows rapidly into hydraulic conduits and there is a fast transfer of energy. Antalya settlement area located on the travertine deposits. Travertine has substantial primary porosity, and often very well-defined karst morphology. The texture of travertine is based upon the conditions of rock formation (sedimentation, atmosphere, and morphology). Travertine has distinctive karstic characteristics, such as hydraulic conduits, large channels of solution, multiple sinkholes, karst springs and dolines and caves that collapse. Water level was defined on each borehole of the several campaigns, being always detected close to the surface. The permeability of the rock mass depends on the degree of weathering and the resulting fractures. Especially the strength of travertines has been compromised by chemical weathering due to increasing pH values in the wastewater [21]. The flow is primarily connected to the fracture system in the slightly weathered rock while the soil is more like a porous medium in the highly weathered material. In the latter case, the porosity of the leaching may have increased, resulting in a very complex groundwater regime along with the highly variable permeability of the rock mass. It is necessary to have the impact of groundwater on characterisation and design. Groundwater pressure and/or flow rate are therefore significant parameters included in the RMR and Q-systems.

2.4. Geophysical uncertainties

Unfortunately, geophysical data is a limited rock mass rating source, but is used to measure elastic parameters, fracture strength, and Q-system and RMR. If the P-wave and S-wave velocities are known, dynamic rock
mass parameters can be evaluated. The seismic method has the best record for the detection of voids and the seismic velocity that indicates the relative strength and weakness of the travertine. The technique is especially sensitive to the presence of clay and water deposits on the subsurface, particularly saltwater. It has been well documented for use in karst regions around the world [22–25] (Table 2). Seismic velocity is typically correlated with relative rock mass density, and density is also correlated with rock strength (Table 1).

Table 1. In-situ karst rock resistance indication based on P wave velocity.

| Zone          | Rock units               | Vp (m/s) | Rock units               | Vp (m/s) | Rock units               | Vp (m/s) |
|---------------|--------------------------|----------|--------------------------|----------|--------------------------|----------|
| I             | Weak travertine          | < 1000   | Surface weathered rock    | 175–525  | Weak travertine          | 659–783  |
| II            | Moderately strong travertine | 1000–2500 | Weathered rock           | 1997–3081| Moderately strong travertine | 1689–1912|
| III           | Massive travertine       | > 2500   | Basal refraction         | 3374–5089|                          |          |

Table 2. Approximate correlation between Q-value and Vp-velocity [28].

| Vp (m/s) | Q  |
|----------|----|
| 1500     | 0.01 |
| 2500     | 0.1  |
| 3500     | 1    |
| 4500     | 10   |

Geotechnical uncertainties

Geology is the principal source of uncertainty in geotechnical engineering. Unidentified ground characteristics may cause unforeseen behaviour, and identified characteristics may not be expressed in quantified terms or their behaviour is not fully known [29]. Geotechnical information is collected and evaluated, the greater the probability of profile correlation and change and the greater the cost savings. Abundant geotechnical complexity involves the study and construction of iterative tunnels. Without reliable geological information, planning decisions could be incorrect [17]. After the initial excavation of the soil cover, geotechnical studies showed karst features such as voids and cavities and areas where the fracturing of the rock matrix greatly weakened the travertine bedrock. The presence of these karst features and unstable rock zones has raised questions about the tunnel and the excavation’s possible stability issues. The investigations included drilling and sampling of the boreholes during tunnel construction to locate voids and travertine zones. For geotechnical purposes, travertine is classified as moderately strong and weak. These travertines differ in thickness and are graded laterally and vertically.

2.6. Uncertainties related to underground structures

Based on the results of the site investigations, a spatial rock mass model can be developed and the expected underground structure can be characterised. Along the tunnel alignment the spatial model is cut and the borders of the lithological units and the fault zones as well as zones of similar influencing factors, such as tunnel shape or primary stress conditions, divide the tunnel alignment into homogenous sections. At this point, geotechnical parameters are set and included in the engineering models. Instead, decisions are made with a degree of doubt, based on their results. When new information is collected, knowledge of the issue in the models can be revised and reused to obtain new findings and make decisions based on less uncertain data. The uncertainty in the measurement of rock mass is largely due to the inherently heterogeneous nature of the rock mass itself. Modern deterministic approaches for evaluating rock mass quality are not focused on a full understanding of these inherent uncertainties, which can adversely affect the overall performance of the material. It is difficult to estimate rock mass strength directly in-situ or by laboratory experiments, and thus several scholars have proposed analytical formulas for estimating rock mass strength. Rock Mass Rating (RMR) [30, 31], Hoek-Brown Relation [32] and Q-System [33] Geological Strength Index (GSI) are among the most commonly used analytical relationships [34]. The uncertainty analysis performed includes determining the accuracy of rock mass based on the Q-system, RMR, and GSI rock mass classification for metro alignment to the 3rd Stage Rail System. The rock masses with different geomechanical properties forming the ground profile in the tunnel line were evaluated based on the Q and RMR rock classification (Tables 3 and 4). NATM Rock Classification [35] has been determined depending on the rock conditions of the tunnel (Table 5). Support types foreseen for these rock classes are described below.

3. Tunnel excavation uncertainties and determination of excavation classes

During the implementation process, general schemes with general instructions are widely used due to the basic features of tunnels and, most of all, due to the complex geological conditions present at various locations. NATM is one of the most popular [36] practices. The entire procedure consists of making the most of the geological strength available in the surrounding rock mass while tunnelling. In order to achieve this goal, an active initial and final liner is constructed, which interacts with the rock mass shortly after its construction.
Table 3. Q-values of rock masses along the tunnel alignment.

| Chainage               | Rock units                  | RQD | Joint set number Jn | Joint roughness number Jn | Joint alteration number Ja | Joint water reduction factor Jw | Stress reduction factor SRF | Q Value | Rock mass quality |
|------------------------|-----------------------------|-----|---------------------|---------------------------|---------------------------|-------------------------------|---------------------------|---------|------------------|
| Km 12 + 045-12 + 521.062 and 12 + 627.582-12 + 801.480 | Moderately strong travertine | 45  | 12                  | 1.5                       | 2                          | 0.66                         | 2.5                       | 0.7425  | Very Weak        |

Table 4. Rock Mass Rating (RMR) values of rock masses along the tunnel alignment.

| Chainage               | Rock units                  | Strength of intact Travertine | RQD (%) | Spacing of discontinuities (m) | Condition of discontinuities | Ground water | Rating adjustment | RMR | Rock mass quality |
|------------------------|-----------------------------|-------------------------------|---------|--------------------------------|------------------------------|---------------|-------------------|-----|------------------|
| Km 12 + 045-12 + 521.062 and 12 + 627.582-12 + 801.480 | Moderately strong travertine | 4                             | 8       | 8                              | 10                          | 15            | −5                | 40  | Weak             |

Table 5. Rock Classification [35] values of rock masses along the tunnel alignment.

| Chainage               | Rock units                  | Q Value | RMR Value | ONORM B2203-1 | Rock support class |
|------------------------|-----------------------------|---------|-----------|----------------|-------------------|
| Km 12 + 045-12 + 521.062 and 12 + 627.582-12 + 801.480 | Moderately strong travertine | 0.7425  | 35        | B3              | A2                |

Table 6. Rock mass scoring along the tunnel alignment.

| Rock Units              | Rock strength | RQD | Joint frequency | Joint condition | Ground water | RMR | GSI |
|-------------------------|---------------|-----|-----------------|-----------------|--------------|-----|-----|
| Moderately strong travertine | 4             | 8   | 8               | 10              | 15           | 45  | 40  |
| Weak travertine          | 2             | 3   | 5               | 8               | 15           | 32  | 28  |

This lining typically takes the form of shotcrete, which is reinforced with a lattice girder and wire, as well as anchors when necessary. Karstic travertine passes over the underground section of the line. They are characterised by karst uncertainties, surface depressions and dissolved voids in small or large rocks. The formation and expansion of these voids poses a major risk to tunnel and underground construction, as they depend on the flow of groundwater and surface waters, which are generally irregularly spread. Karst cavities are interconnected during the dissolution cycle and enable the surface waters to enter the aquifer. The dissolution cycle begins and over time the karst cavities expand. Dissolution voids of 1–5 metres in the alignment, which in places are filled with clay deposits, can cause problems in time and the clay floors in the hollow ceiling structures can be mobilised in the form of excessive demolition or spillage during tunnel construction. Notwithstanding this, and the need to fill these holes in tunnel excavation by injection, the support class was referred to as “A2 special type” and, in addition to the support class A2 type, it was deemed appropriate to apply for “injection time”. In this case, it is important to compare the volumes of karst cavities determined from the front and the amount of injection used to fill these cavities with the related quality controls in all injection applications to decide on the establishment of the desired impermeable solid structure and to start the tunnel construction. The tunnel on the project route, which is planned to be built using the NATM method, is the main line tunnel “A2 Type and A2 Special Support Type”. Geotechnical database obtained from the relevant research studies, the RMR and GSI was obtained (Table 6). According to NATM classification [35], the tunnel was excavated in B3 rock class. However, as a result of evaluating the ground, tunnel dimensions, cover thickness on the tunnel and environmental conditions together, the rock support class of the tunnels to be opened in the relevant section interval was evaluated as A2. In this context, it is envisaged to support the tunnels with the “A2 Type” or “A2 Special Type” support type corresponding to the class. The reason for applying “A2 Special Type” section is that the tunnels were built on karstic ground.

These calculations take into account the range, length, span, roughness, bank, weathering, groundwater, the rock quality indicator and the strength of the rock material. In addition, laboratory data on the selected uniaxial compressive strength and unit weight were evaluated for the rocks forming the tunnel floor. Table 7 summarises data such as the GSI, Hoek-Brown constant of intact rock (mi), disturbance factor (D) and the elasticity modulus (E).

Cohesion (C), internal friction angle (Φ), unit volume weight (γ) and deformation module (E) values for the sectional analysis to be used in tunnel design are summarised in Table 8.
Table 7. Selected rock mass parameters along the tunnel alignment.

| Rock units           | Uniaxial Compressive Strength (MPa) | Geological strength index (GSI) | Hoek-Brown constant of intact rock (mI) | Elasticity modulus (Ei) (MPa) | Unit weight (kN/m$^3$) | Disturbance factor (D) |
|----------------------|-------------------------------------|---------------------------------|------------------------------------------|-------------------------------|------------------------|-----------------------|
| Moderately strong travertine | 15                                  | 40                              | 10                                       | 8000                          | 23.50                   | 0.70                  |
| Weak travertine      | 5                                   | 28                              | 9                                        | 3000                          | 23.50                   | 0.30                  |

In addition, the cohesion (c), internal friction angle ($\Phi$), unit volume weight ($\gamma$) and deformation module (E) values of the different rock and ground units selected for tunnel section analysis of support systems in the predicted critical sections are summarised in Table 9. Tunnel stabilisation analyses have also been performed using these data. For tunnel stability study, the PLAXIS finite element program and the “Hardening Soil” model, which can model the plastic behaviour of the soil, have been used (Figure 3).

Although the 960-metre long excavation of the double underground tunnel has been completed, concrete work is ongoing. Isolation work is also carried out in tunnels. Excavation is performed at the West Station, at a depth of 27 metres, where underground tunnels are connected (Figure 4(a,b)).

Table 8. Rock mass parameters along the tunnel alignment.

| Rock units | Depth (m) | $\gamma$ (kN/m$^3$) | C (kPa) | $\Phi$ (°) | E (MPa) |
|------------|-----------|----------------------|--------|------------|---------|
| Moderately strong travertine (8.00 m) | 8 | 23.5 | 47 | 41 | 358 |
| Moderately strong travertine (22.00 m) | 22 | 23.5 | 64 | 37 | 358 |
| Weak travertine | 5 | 23.5 | 18 | 43 | 149 |

Table 9. Rock mass parameters.

| Chainage | Rock units | C (kPa) | $\Phi$ (°) | $\gamma$ (kN/m$^3$) | E (MPa) |
|----------|------------|--------|------------|---------------------|---------|
| Km 12 + 045 | Fill | 5 | 30 | 19 | 15 |
|           | Weak travertine | 18 | 43 | 23.5 | 149 |
|           | Moderately strong travertine | 47 | 41 | 23.5 | 358 |
| Km 12 + 365 | Fill | 5 | 30 | 19 | 15 |
|           | Weak travertine | 18 | 43 | 23.5 | 149 |
|           | Moderately strong travertine | 64 | 37 | 23.5 | 358 |
| Km 12 + 405 | Fill | 5 | 30 | 19 | 16 |
|           | Weak travertine | 18 | 43 | 23.5 | 149 |
|           | Moderately strong travertine | 64 | 37 | 23.5 | 358 |

Figure 3. Displaying the results of the 12 + 045 section of analysis of the PLAXIS finite element program [37].
4. Conclusions

Uncertainty is one of the most important aspects of tunnel design and underground construction. Moderately strong and weak travertines were excavated during the Antalya 3rd Stage Rail System Project tunnel and cut-cover construction. This has low strength and high deformation due either to weak consolidation or cementation or extreme weathering. The mass properties of Antalya travertines are quite variable. Wastewater originated in residential units and industries connected to septic discharge holes. These septic holes allow the wastewater to percolate through cracks in the travertine below for several years. Wastewater has negative effects on travertine mass and material properties. Due to the lithological uncertainty of travertines, the design and construction of tunnels and underground structures in moderately strong and weak travertine formations has created a variety of problems for geotechnical engineers. The engineering properties of moderately strong and weak travertines were determined in the laboratory. After than, a quantitative, probabilistic approach has been taken to the use of the Q, RMR and GSI systems for rock mass characterisation. Based on experimental work, field and laboratory tests, the rock mass classification and deformation modules were investigated by Q, RMR and GSI systems. RMR values show that moderately strong and weak travertine with values ranging from 32 to 45 along the tunnel alignment. While Q values are 0.7425 tunnel alignment with covering a very weak quality rock. According to NATM classification, the tunnel was excavated in B3 rock class. However, as a result of evaluating the ground, tunnel dimensions, cover thickness on the tunnel and environmental conditions together, the rock support class of the tunnels to be opened in the relevant section interval was evaluated as A2. In this context, it is envisaged to support the tunnels with the “A2 Type” or “A2 Special Type” support type corresponding to the class. The reason for applying “A2 Special Type” section is that the tunnels were built on karstic ground.

Using the finite element method and the PLAXIS software, measurements of the temporary and permanent tunnel support system have been carried out. During the determination of the study pieces, the thickness of the tunnel, the groundwater level, the units where the tunnels will be opened and the structures in the tunnel were taken into account. Analyses have been made for these pieces. The results show that tunnel design and underground construction in karstic travertine areas require careful planning from the design stage to the construction stage; where continuous input from the construction team and design team is required to ensure successful construction and satisfactory performance of foundations. However, it is critically important to consider the geological, hydrogeological, geophysical and geotechnical uncertainties of travertines in the tunnel works in the continuation of the project.

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ORCID

Mehmet Ozcelik http://orcid.org/0000-0003-4511-1946  
Merih Can Aydemir http://orcid.org/0000-0001-8102-7181

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