Predictable and Unpredictable Uncertainties Delaying the Completion of the Kabatas-Mahmutbey Metro Construction (Istanbul / Turkey)

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ABSTRACT: The design and construction of tunnels is among the most specialized fields in underground engineering. There are various uncertainties during tunnel excavation. Predictable and unpredictable uncertainties are important sources of risk in tunnel engineering. The effect of uncertainty on risk assessment and decision-making is therefore provided priority, particularly for tunnel projects where predictable uncertainty is often the primary cause of risk. First phase of the Kabatas-Mahmutbey tunnel excavation, some collapses occurred due to uncertainties in different parts of the tunnel route. Regardless, Kabatas-Mahmutbey metro line, which is 24.5 km long and consists of 19 stations, was planned to be operational in the first quarter of 2020. For this purpose, electrical and mechanical tests were successfully continuing within the scope of the project. In addition, the signalling works of the metro line were near to the end. All technical uncertainties and risks were thought to be circumvented. In the last phase of the project, Coronavirus Disease 2019 (COVID-19) was encountered as unpredictable uncertainty. Unfortunately, due to COVID-19, the work in the project has been postponed to a later date. With the commissioning of the metro project, which will breathe the traffic of Istanbul upon commissioning, it is foreseen to carry 500 thousand passengers a day.

KEYWORDS: Uncertainty, Tunnel, Construction, 3D Modelling, COVID-19.

1. INTRODUCTION

The tunneling community has acknowledged the need to analyze the uncertainty and hazards associated with tunnel construction (Lombardi, 2001; Eskesen et al., 2004; Reilly, 2005; ITIG, 2006; Ozcelik, 2020). Predictable and unpredictable uncertainties are important sources of risk in tunnel engineering. Construction time and cost estimate uncertainty is the result of normal changes in construction efficiency and exceptional incidents such as collapses of tunnels (Isaksson and Stille, 2005). Several methods have been proposed to estimate, quantify and display uncertainty over the past decade (Tacher et al., 2006; Pennington, 2011; Lark et al., 2013; Lindsay et al., 2014; Kinkeldey et al., 2017). On the other hand, the probability of a construction failure is often independently evaluated using techniques such as fault tree or event tree assessment, decision trees or risk matrices (Shahriar et al., 2008; Hong et al., 2009; Aliahmadi et al., 2011; Sousa and Einstein, 2012; Spackova et al., 2013). Previously, several writers suggested estimating, quantifying and visualizing uncertainty (Wellmann et al., 2010; Wellmann and Regenauer-Lieb, 2012; Wellmann, 2013; Lindsay et al., 2014; Schweizer et al., 2017). These studies conducted to date were known as technical uncertainties. A group of uncertainties is widely cited as technological uncertainties. The four levels of technical uncertainty are classified by Shenhar (2001): low, medium, high and super high. Lechler et al. (2012) also note that projects are subject to unforeseen uncertainties even with rigidly planned technical specifications. COVID-19 was confronted with volatile ambiguity in the last phase of the project. COVID-19's global distribution causes unparalleled delays, disruptions and challenges for megaprojects. Travel constraints, social distancing and quarantines are constantly affecting supply chains, contracting workers and the availability of project inspection government resources, resulting in delays and higher costs. This paper provides advice to developers and owners concerned with COVID-19-affected projects and highlights measures that should be taken to minimize the effects of the project. In the present pandemic situation, metro building, like many industries, is facing unprecedented chaos. Contractors are facing even greater obstacles today, with ever-changing uncertainty and government legislation to temporarily obstruct projects. Although risk management is a complex activity involving mitigation of legal or client-specific risk, with the widespread consequences of COVID-19, particularly in terms of performance bond claims, this has become more than ever a critical problem to look at now. In this study, risks arising from technical uncertainties in different parts of the tunnel route were investigated during the Kabatas-Mahmutbey tunnel excavations. While the technical uncertainties and risks were thought to have been overcome, the work in the project was postponed to a later date due to COVID-19. With this result, it is inevitable that uncertainty and risks always appear in different situations.

2. METHODS

The number of construction projects around the world is continuously increasing, along with changes in human lifestyles and technologies. In underground construction, it is difficult to expect some underground responses to excavation actions due to the complexity and the heterogeneity of the surrounding medium (Zhang et al., 2017). Uncertainty is a condition containing predictable and/or unpredictable details in which it can be difficult to accurately characterize the actual condition, the potential outcome, or more than one possible outcome. It occurs in partially measurable and/or stochastic settings that correspond to forecasts of future events, physical measurements already produced, or uncertain measurements. In many areas of engineering and science, uncertainty analysis is becoming increasingly common (Cacuci and Ionescu-Bujor, 2004). Geological, geotechnical, hydrogeological and tunnel excavation uncertainties are the primary sources of predictable uncertainty in tunnel engineering (Ozcelik, 2020). There are always uncertainties in these parameters, some of which are internal, some of them due to the fact that these parameters are not known or not understood. The presence of these uncertainties entails the need to assess the models' reliability. Uncertainty is essential to informed, risk-conscious, decision-making when used as the grounds for expressing accuracy (Xia et al., 2017; Pakyuz-Charrier et al., 2018). Predictable uncertainties are investigated in the current case because they usually contain more uncertainty for the case study, and this research first tries to show the importance of technical uncertainties and their application by focusing on tunnel excavation research. Unpredictable COVID-19, which emerged in the last phase of the project, was a significant risk apart from the known uncertainties.

2.1 Predictable and Unpredictable Uncertainties

Two types of tunneling methods are implemented in the Istanbul Metro Project between Kabataş-Mahmutbey stations. These are

Tunnel Boring Machines (TBM) and the New Tunneling Method for Austria (NATM). The overall length of the two tunnel lines to be opened using TBM is 24.5 km (Figure 1).

Figure 1 Main route of Kabatas-Mahmutbey Metro Line

2.1.1 Predictable Uncertainties

Tunneling in this densely populated urban area is connected with a number of issues such as absence of station space and access shafts (more than 20 access shafts are required), interference with precious structures and the need to preserve traffic during building on critical highways. In addition, the complicated contractual limitations, the heterogeneous geological conditions consisting primarily of sedimentary rocks with volcanic intrusions, and the region's elevated amount of seismicity pose a major challenge to the designers and contractors. In urban areas, tunnel planning and development have their own specific problems and risks (You et al., 2005; Andreottia and Lai, 2019). The main predictable uncertainties are identified as follows: geological, geotechnical, hydrogeological uncertainties, tunnel excavation uncertainties and risk of extraordinary events.

Geological uncertainties: Geological uncertainties can also be created by insufficient ground conditions understanding, which is the primary reason for issues with geotechnical design (Baecher and Christian, 2003; Thornton et al., 2018). In order to better understand geological structures, 3D models have been used to reduce uncertainties in many geological areas (Houlding, 1994; Wu et al., 2005). Kabatas-Mahmutbey tunnels are excavated in two different geological formations (Figure 2). Trakya Formation consists predominantly of an alternation of sandstone, siltstone and claystone with limestone lenses, andesite and diabase dykes. Also, layers of limestone and conglomerates are seldom situated. Dykes of andesite and diabase are about 2-3 m thick and rarely reach 50-60 meters. The first 15-20 meters of the Trakya Formation is weathered, medium weathered and the lower sections are grey-blue colored unweathered rock. According to regional data, the thickness of the formation is more than 1000 meters. Ceylan Formation is noted in the western alignment of the tunnel, which consists of a multitude of calcareous clay, clayey calcareous, clayey sand (Ozcelik, 2018).

It is presumed that a big number of distinct data types are required by 3D geological models. It is difficult to deal with geological uncertainty by using sparse or widely dispersed data when showing the geological structure (Kauffman and Martin, 2008; Carrera et al., 2009; Caumon et al., 2009; Hou et al., 2016). 3D visualization methods have been applied in many fields such as geology, geotechnical engineering, hydrogeology, environmental geology, prospecting and exploration for mineral resources, and numerical simulations of rock mechanics. In short, the geological, hydrogeological and structural parameters modelled by the 3D visualization method will reduce the interpretation of the environment to a simpler and more meaningful one (Figure 3).

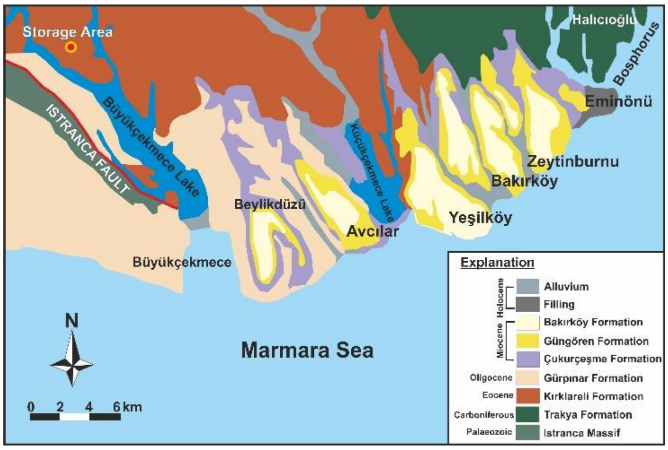

Figure 2 Geological map of Istanbul's European side (modified according to Lom et al., 2016)

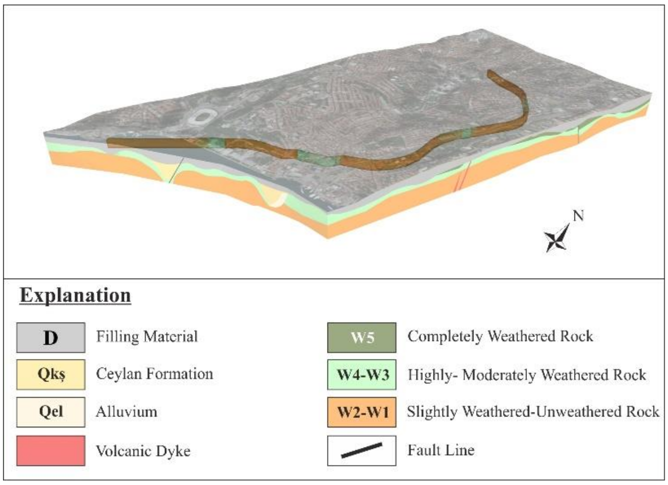

Figure 3 Displaying of 3D visualization model

Geotechnical uncertainties: Geotechnical uncertainty is often the most significant source of risk associated with a project in underground construction and tunneling works. Unforeseen adverse geotechnical conditions can lead to major construction problems, resulting in decreased tunnel advance rates and delays in scheduling, cost increases, damage to existing facilities, and/or damage to construction equipment. Geotechnical risk control is a critical concern with any underground undertaking, and some degree of stability and sensitivity must be provided in the design process to mitigate the expensive consequences of unexpected conditions (Baynes, 2010). For this purpose, more than 50 boreholes were drilled in the Kabatas-Mahmutbey tunnel line and samples were taken. Q system (Barton, 2002), Geomechanics Classification System (RMR) (Bieniawski, 1988), Geological Strength Index (GSI) (Hoek et al., 1998) and ONORM B 2203-1 (Austrian Standards Institute, 2001) were used for rock mass classification processes for engineering applications. The geotechnical features of the structures discovered along the tunnel alignment were defined by laboratory and in situ studies (Table 1). Based on lithology and distinct weathering concentrations, the rocks in the tunnel path are categorized according to the Q, RMR and GSI rock mass classification schemes. The findings of the classification are shown in Table 2.

Table 1 Engineering Properties of the Geological Formations on the Tunnel Route (AGEC 2016b)

Formation characteristics		**Geotechnical Properties**					
			Strength parameters			**Deformation parameters**	
Formation	**Unit**	**Unit weight**	**Cohesion c**	**Uniaxial Compressive Strength**	**Internal friction angle Ø**	**Young modulus E**	**Poisson ratio υ**
		kN/m³	**kPa**	**MPa**	**(○)**	**N/m²**	
Ceylan Formation	Clay (Hard)	26.0-27.7		18-28			0.12-0.28
	Clay (Hard)-Claystone	28.6-28.9		67-185	30-34		0.16-0.22
	Clayey Sand	24.5-27.4		32-47	20-26		0.23-0.30
	Sandy Clay	27.8-28.0	18-20	15-18	11-15		0.14-0.20
Trakya Formation	Sandstone	26.3-28.4		40-165	40-56	4.9-5.40	0.23-0.29
	Siltstone	23.5-27.6		15-25	30-35		0.28-0.26
	Claystone	23.4-27.6		12-17	20-55	1.90-4.58	0.20-0.24

Table 2 Classification of Rocks Along the Tunnel Alignment (AGEC, 2016b)

Rock Unit	**Rock mass properties**	**Q**	**RMR**	**GSI**	**ONORM B 2203-1**
Trakya Formation Highly – Moderately weathered Rock (W3-W4)	Claystone - sandstone - siltstone alternation (fragmented)	0.08 Very poor rock	26-31 Weak Rock	30	C2-B3
Trakya Formation Slightly weathered – Unweathered Rock (W1-W2)	Claystone - sandstone - siltstone alternation (frequently fractured-fragmented)	0.31 Very poor rock	31-36 Weak Rock	40	B3

Hydrogeological uncertainties: In conceptualizing and trying to simulate groundwater flow in these environments, the visualization of the 3D geological model is crucial. The hydrogeologically impermeable-less permeable property of the Trakya Formation, which constitutes most of the study field. On the western side of the site, the Ceylan Formation is located above the Trakya Formation. Clayey units are generally dense and impermeable in Ceylan Formation. The lower levels are composed of gravel and sand. It may be partially permeable. In the pressurized water tests performed in the Trakya Formation, the Lugeon values were predominantly impermeable (< 1 Lugeon) and a small percentage was found to be less permeable (1-5 Lugeon). It was not predicted that groundwater would be detected during the excavation.

Tunnel excavation risks: Tunnel designs are highly complex and are related to a variety of uncertainties owing to geographical and geotechnical conditions, exterior loading and construction efficiency. During tunneling, these uncertainties can lead to future hazards for both the employees and the environment around them. In urban regions, surface settlements induced by tunnel excavation may be particularly important, with higher significance in blended soil circumstances. Some of the most difficult topics in mechanized tunneling are mixed ground conditions (Figure 4(a) and 4(b)). In this condition, water intake, face collapse, and squeezing floor are very prevalent issues. The region of the project contains very complex geological systems, including the formation of Trakya and the formation of Ceylan. The Lower Carboniferous is characterized by the Trakya Formation, which primarily consists of interbedded sandstone, siltstone, mudstone or as separate units along with intrusions into the dyke. Limestone and layers of conglomerates are also seldom observed. In this fragile structure, about 95 percent of the tunnel drive is present. It consists of calcareous clay, clayey calcareous, clayey sand at the foundation and sandy clay.

(a)

(b)

Figure 4 (a) Collapses some parts of the tunnel alignment and (b) Collapses some parts of the tunnel alignment

Selection of the tunnel's method as digging a tunnel should be made to comprehensive review of the safety, economy, ease of construction such as the construction based on the geological conditions excavation target portion. Recent tunnel construction method most preferred is exemplified by NATM method, TBM method (Mix Shield, EPB Shield, Single Shield and Gripper TBM) with the conventional method. The NATM construction method is therefore withstand a heavy load, even if the stand the holding allows the ground itself, the periphery of the tunnel, as described above to act as a holding, is advantageous in that it can be a tunnel construction, regardless of the influence of soil and ground. TBM method is a method utilizing mainly during construction tunnel in blasting operation is impossible region (tunnel, ground is weak area) by the normal powder loading. The TBM method is capable of digging into the front end non-blasting, vibration-free manner using a tunneling machine called TBM. NATM and the TBM are used to build these metro tunnels. The main metro line tunnels are planned to be built by TBMs. Metro station platform tunnels, switch tunnels and the connection tunnel are planned to be built by NATM because of the different section.

2.1.2 Unpredictable Uncertainties

Risk of extraordinary events: China, Indonesia, Iran and Turkey have the most catastrophic earthquakes with high death rates and destruction. They are associated with the frequent occurrence of earthquakes and are typically associated with difficult and weak geological conditions, which pose design difficulties but can also create issues during the excavation of tunnels. Earthquakes occurred during the building of the tunnel, which contributed to significant damage and delays. In a seismically active area, the Kabatas-Mahmutbey metro tunnel alignment is located about 21 to 23 km away from the NAFZ. Two dynamic seismic joints / segments with displacement limits of ±50 mm for shear and ±75 mm for extraction/contraction were specially engineered and placed near to both ends of the segment in marine sediments in order to reduce seismic stress/strains below permissible concentrations. In the event of an earthquake, the behavior of the tunnel was planned for Mw = 7.25 and earthquakes were analyzed for return periods of 500 and 2500 years for operation and safety assessment, respectively (Kulhawy and Mayne, 1990).

Health and safety risks related uncertainty assessment: The COVID-19 pandemic and its related effects on economies and economic development face a variety of challenges for the engineering and construction sectors – challenges that could deepen internationally based on the magnitude and extent of the crisis. It is difficult for the industry to foresee how the recovery will proceed because of uncertainty about the duration and nature of the crisis. Many engineering projects have been postponed and some have been cancelled as a result of the effects of COVID-19 on the businesses and governments that commissioned them. In addition, possible supply chain bottlenecks in infrastructure and supplies, including structural steel and glass, may lead to delays in projects currently financed or to a reduction in spending on potential projects. The opening of the Kabatas-Mahmutbey metro, which entered its final level, was negatively impacted by COVID-19.

Risk of increased project costs: COVID-19 creates significant risks, particularly in terms of schedule, cost and quality, for the construction industry. They are either extended or accelerated when programs are postponed, and thereby incur extra costs. Therefore, delays in construction projects cause all parties involved to be frustrated, and the project manager's key role is to ensure that projects are finished within the time and expense of the budget. Practitioners need to cultivate the ability to predict possible challenges that their current and future ventures are likely to encounter. It is a good choice to recognise the common problems faced by previous projects in their construction business setting.

3. CONCLUSIONS

Uncertainty is one of the most critical aspects of underground engineering. In this article, the two major classes have been divided into uncertainties. Predictable and unpredictable uncertainties and its impact on decision-making, especially given the increasing uncertainty often a priority for large engineering projects such as tunnels to be the main source of risk. Predictable technical uncertainties of Kabatas-Mahmutbey metro tunnels were analyzed during construction period. Comparisons of the real images with the model, marked through 3D models, facilitated it to identify geological structure. Although project uncertainties data possess a variety of values in a big range, which is much suitable for interpretation and identification of the results. The lack of drilling at frequent intervals along the tunnel route was considered a deficiency. It is very useful to have coordinates of data in areas beyond the special geological features. Obviously then those all could have the more engineering data and therefore gridding would be performed with more reliable results. Geological uncertainties including faults, dykes, and tunnel path was evaluated efficiently with 3D model. The combined 3D visualization showed the overall geometric connection of flaws, dykes, tunnels and topography. During the construction phase of the subway, technical uncertainties and risks on the Kabatas-Mahmutbey metro line were assessed for this purpose. But unexpectedly, the COVID-19 emerged in the last phase of the subway construction as seen unpredictable uncertainties. Electrical and mechanical tests at the last stage could not be completed and the opening of the project was postponed. The COVID-19 epidemic is triggering global concern and economic distress for customers and enterprises across the globe. The crisis is quickly emerging, with widespread consequences.

4. ACKNOWLEDGEMENTS

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