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Tunnel Construction: Time Scenarios by Risk Level

Stefani Gjorgjevska[a], Zlatko Zafirovski[b] and Vasko Gacevski[b]*

[a] Civil Engineering Institute Macedonia, Skopje, Republic of North Macedonia; stefani.gjorgjevska@gim.com.mk
[b] Ss. Cyril and Methodius University in Skopje, Faculty of Civil Engineering, Skopje, Republic of North Macedonia; zafirovski@gf.ukim.edu.mk, gacevski@gf.ukim.edu.mk

Abstract: This study investigates the construction duration of 124 tunnel segments along the Pan-European Railway Corridor VIII in the Republic of North Macedonia, focusing on the impact of rock types according to the S classification. Employing a quantitative research approach, the study develops three risk scenarios (low, medium, and high) based on geological characteristics, including rock strength, fracture presence, and hydrogeological conditions. The S classification, adapted to local geological conditions, aligns with international systems such as the Q system and RMR (Rock Mass Rating). The analysis involves calculations of construction duration per meter and total duration for each scenario, using data from field surveys, geotechnical reports, and project documentation. Results indicate that in Scenario 1 (low risk), the average construction duration is 1.9 days/m, in Scenario 2 (medium risk) 4.3 days/m, and in Scenario 3 (high risk) 7.9 days/m, resulting in total durations of 359, 753, and 1359 days, respectively. The comparison shows a 109.75% increase in Scenario 2 and a 278.55% increase in Scenario 3 compared to Scenario 1. These findings facilitate improved planning, resource optimization, and enhanced safety in tunnel engineering, particularly in regions with complex geology. The study also discusses the limitations of assuming a single rock type and the potential influence of factors such as excavation methods and crew experience.

Keywords: tunnel; tunnel construction; construction time duration; risk;

1. Introduction

Tunnels are underground structures designed to overcome terrain obstacles and to ensure the technical elements of the road on which they are planned and constructed. A tunnel is an underground passage created by humans without removing the upper layers of soil and rock. A key characteristic of a tunnel is that it is a structure built beneath the surface of the terrain.

In a broader sense, the term "tunnel" also refers to larger underground spaces intended for energy or other facilities, garages, commercial spaces, warehouses, shelters, sports facilities, permanent underground mining rooms, and underground landfills for hazardous waste.

This study examines the impact of rock classification on the construction duration of 124 tunnel segments along the Pan-European Railway Corridor VIII in the Republic of North Macedonia. Its unique contribution lies in developing three risk scenarios (low, medium, and high) based on the S classification, enabling precise prediction of construction duration and resource optimization. This approach contributes to enhanced planning and safety in tunnel engineering in regions with complex geology, which is particularly relevant for projects like the Pan-European Corridor VIII.

Risk is a calculated forecast of potential damage, or in a negative case, loss or danger. The level of risk is a function of the probability and severity of the damage. Most risks in tunnels arise from the fact that hazardous events occur in a space that is almost completely enclosed and usually connected to the open space only through the two tunnel portals. The effects of the "enclosed space" are particularly pronounced in long tunnels when the accident site is far from the portal.

*Corresponding author: stefani.gjorgjevska@gim.com.mk (S. Gjorgjevska).

General risks:

- Risk before tunnel construction;
- Risk during tunnel construction;
- Risk during tunnel operation.

Types of risks can be categorized into three basic types:

- Completion risk, where there is a danger that the project will not be finished within the planned timeframe;
- Cost risk, where there is a possibility that the project costs will exceed the planned budget;
- Performance risk, which refers to the possibility that the project outcome will contain technical flaws that may lead to problems and project losses.

This paper presents an analysis of the construction time of 124 tunnel segments that are part of the Pan-European Railway Corridor VIII in Republic of North Macedonia.

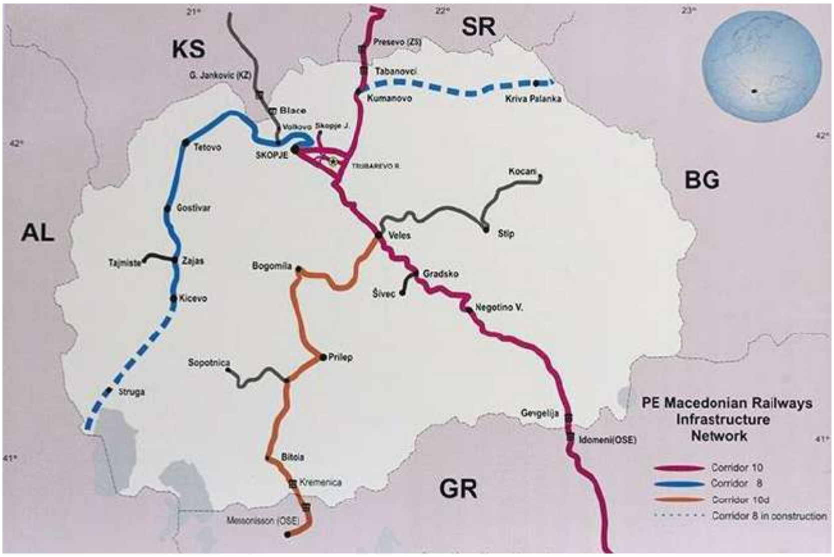

Fig. 1. Pan-European Corridors on the territory of Republic of North Macedonia.

The analysis aims to examine the impact of different rock types according to the S classification and the corresponding variation in tunnel construction time. The purpose of this analysis is to support efficient planning and execution, ensure safety during construction, and optimize the use of resources and budget.

The rock class has a significant influence on the excavation of tunnel segments and, consequently, on the total construction time of the tunnels, as it allows for the creation of a realistic construction schedule.

The S classification of rocks includes several categories, where SI represents the strongest and most stable rock, while category SVII or higher represents the weakest and most unstable rock. The rock classification is based on: rock strength, cracks, hydrogeological conditions, and overall rock mass condition.

The scenarios developed in this analysis are:

- Scenario 1 – Low risk;
- Scenario 2 – Medium risk;
- Scenario 3 – High risk.

The first scenario, or low-risk scenario, involves the most favorable rock conditions. The tunnels that are part of the first scenario have the most optimal working conditions, with minimal construction risks, which in turn results in the shortest construction time. By analyzing the segments and comparing the construction time of the tunnel by individual segments versus when the segments are classified under the first, low-risk scenario, a reduction of approximately 35% in total construction time is achieved.

The second scenario, or medium-risk scenario, includes moderate challenges. The tunnels that are part of the second scenario are the most common in real-world projects. They are positioned somewhere between Scenario 1 and Scenario 3, that is, between ideal and unfavorable conditions. By analyzing the segments and comparing the construction time of the tunnel by individual segments versus when the segments are classified under the second, medium-risk scenario, an increase of approximately 35% in total construction time is observed.

The third scenario represents high risk, with the least favorable conditions for the construction of the tunnel segments. The third scenario includes tunnels with unfavorable construction conditions and represents significant challenges for engineers. These tunnels are characterized by unstable geology, which leads to an increase in construction time compared to initial estimates. By analyzing the segments and comparing the tunnel construction time by individual segments versus when the segments are classified under the third, high-risk scenario, an increase of approximately 130% in total construction time is observed.

2. Overview of Available Data

Data for the 124 tunnel segments were collected from field surveys, geotechnical reports, and design documentation for the Pan-European Railway Corridor VIII. Each segment is characterized by: (1) segment length, (2) excavation method (e.g., mechanical excavation or blasting), (3) construction duration, and (4) rock type according to the S classification. Risk scenarios were assigned based on geological characteristics, including rock strength, fracture presence, and hydrogeological conditions. In cases of incomplete data, estimates were based on average values from similar segments or expert judgments from project reports. Data on excavation methods were derived from project documentation, with mechanical excavation predominant in stable rocks (SI-SIII) and blasting more common in unstable rocks (SVII).

2.1. Definition of S Classification and Risk Scenarios

The S classification is a rock categorization system based on rock strength, degree of fracturing, hydrogeological conditions, and overall rock mass condition. Category SI denotes strong, stable rocks with minimal fractures and favorable hydrogeological conditions, while SVII represents weak, unstable rocks with significant fractures and adverse conditions, requiring enhanced support and slower excavation methods. This classification aligns with international systems, such as the Q system and RMR (Rock Mass Rating), but is adapted to local geological conditions in North Macedonia.

Risk scenarios were defined based on the following criteria:

- Low Risk (Scenario 1): Rocks from SI to SIII, with high strength, minimal fractures, and no significant hydrogeological challenges, allowing rapid excavation with minimal support;
- Medium Risk (Scenario 2): Rocks from SIV to SVI, with moderate strength, moderate fractures, and occasional hydrogeological issues, requiring additional stabilization measures;
- High Risk (Scenario 3): Rocks from SVII or weaker, with low strength, intense fracturing, and complex hydrogeological conditions, increasing construction time due to enhanced support needs and collapse risks.

3. Methodology

In the book "Research Design: Qualitative, Quantitative, and Mixed Methods Approaches" (2014) by John W. Creswell, the three main research approaches—qualitative, quantitative, and mixed methods—are thoroughly explained. These approaches are discussed in the context of their application, philosophical foundations, and practical implementation.

- The qualitative method focuses on understanding individual experiences, meanings, and social processes;
- The quantitative method emphasizes the measurement and analysis of numerical data to test hypotheses or determine statistical relationships;
- The mixed method combines both qualitative and quantitative approaches to provide a more comprehensive understanding of the research question.

The research in this paper is focused on data analysis and graphical representation of results for different tunnel segments, utilizing the quantitative research method.

According to Creswell, quantitative research is defined as “the collection, analysis, and interpretation of numerical data to explain phenomena.”

In this analysis, based on the available data, each tunnel segment includes three different types of rock according to the S classification. The analysis includes a prediction of how many days it would take to construct the tunnel if it were entirely composed of a single type of rock. Therefore, three scenarios were developed, each calculating the total construction time of the tunnel assuming it is entirely in rock material from segment 1, segment 2, or segment 3.

Based on the obtained data, the following calculations were made:

- Total tunnel length:

$$\textit{Total tunnel length} = \textit{Sum of the lengths of all segments [m]} \tag{1}$$

- Construction duration per meter:

$$\textit{Duration per meter} = \textit{Construction time / Length of segment [days/m]} \tag{2}$$

- Construction time:

$$\textit{Construction time} = \textit{Total length} \times \textit{Duration per meter [days]} \tag{3}$$

Tunnel construction duration is influenced not only by rock type but also by excavation methods, the experience of construction crews, and the use of specialized mechanical equipment. For example, mechanical excavation using tunnel boring machines (TBM) is faster and more efficient in stable rocks (SI-SIII), while blasting is more common in unstable rocks (SVII), increasing construction time due to the need for additional stabilization measures. Crew experience affects work efficiency, particularly in complex geological conditions, where skilled teams can reduce construction time. Equipment efficiency and availability also play a critical role, with modern equipment potentially accelerating the process compared to outdated technology. These factors were not fully analyzed in this study due to data limitations but were considered in interpreting the results to ensure practical applicability. To enhance the analysis’s accuracy, excavation method data were categorized based on project documentation, with the percentage of mechanical excavation and blasting specified for each segment.

The following tables present a portion of the tunnel segments along with the calculations made for them by scenario:

Table 1. Scenario 1 – Low risk.

Tunnel No.	Section No.	Length [m]	Construction time of segments [day]	Tunnel construction time [day]	Total tunnel length [m]	Percentage type of substructure	Duration per meter [m/day]	Constuction time [day]
	1	119.50	155					
1	2	42.68	160	375	170.71	SI 70%	1.3	222
	3	8.54	60					
	4	35.06	46					
2	5	26.30	98	303	87.66	SI 40%	1.3	114
	6	26.30	159					
	7	36.91	45					
3	8	88.59	300	489	147.65	SI 25%	1.2	181
	9	22.15	143					
	10	35.79	47					
4	11	20.88	78	143	59.65	SI 60%	1.3	78
	12	2.98	18					

Table 2. Scenario 2 – Medium risk.

Tunnel No.	Section No.	Length [m]	Construction time of segments [day]	Tunnel construction time [day]	Total tunnel length [m]	Percentage type of substructure	Duration per meter [m/day]	Constuction time [day]
	1	119.50	155					
1	2	42.68	160	375	170.71	SVI 25%	3.7	639
	3	8.54	60					
	4	35.06	46					
2	5	26.30	98	303	87.66	SVI 30%	3.7	328
	6	26.30	159					
	7	36.91	45					
3	8	88.59	300	489	147.65	SVI 60%	3.4	500
	9	22.15	143					
	10	35.79	47					
4	11	20.88	78	143	59.65	SVI 35%	3.7	223
	12	2.98	18					

Table 3. Scenario 3 – High risk

Tunnel No.	Section No.	Length [m]	Construction time of segments [day]	Tunnel construction time [day]	Total tunnel length [m]	Percentage type of substructure	Duration per meter [m/day]	Constuction time [day]
	1	119.50	155					
1	2	42.68	160	375	170.71	SVII 5%	7.1	1205
	3	8.54	60					
	4	35.06	46					
2	5	26.30	98	303	87.66	SVII 30%	6.0	529
	6	26.30	159					
	7	36.91	45					
3	8	88.59	300	489	147.65	SVII 15%	6.5	955
	9	22.15	143					
	10	35.79	47					
4	11	20.88	78	143	59.65	SVII 5%	6.0	360
	12	2.98	18					

At the end of this calculation, the average construction duration per meter was calculated for each scenario across all 124 tunnel segments.

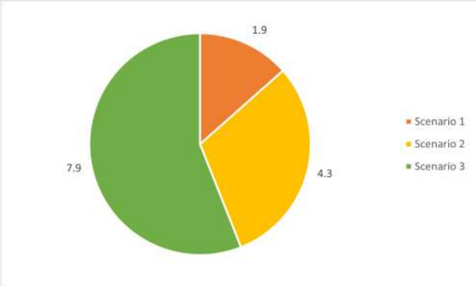

Fig. 2. Average construction duration per meter.

Additionally, the average total construction time of all tunnel segments was calculated for each scenario.

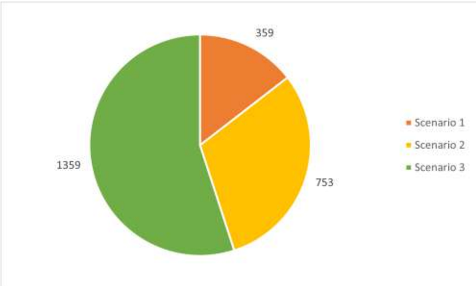

Fig. 3. Average total construction time.

4. Results

The analysis of 124 tunnel segments from the Pan-European Railway Corridor VIII reveals significant variations in construction duration based on risk scenarios, driven by the geological characteristics of rocks according to the S classification. In Scenario 1 (low risk), involving rocks from SI to SIII with high strength and minimal fractures, the average construction duration per meter is 1.9 days/m, resulting in a total duration of 359 days for all tunnels. In Scenario 2 (medium risk), which includes rocks from SIV to SVI with moderate strength and occasional hydrogeological challenges, the duration per meter increases to 4.3 days/m, with a total duration of 753 days. In Scenario 3 (high risk), involving rocks from SVII or weaker with intense fracturing and complex hydrogeological conditions, the duration per meter is 7.9 days/m, leading to a total duration of 1359 days. These results are illustrated in Figure 2 (average construction duration per meter) and Figure 3 (total construction duration).

The comparison shows that Scenario 2 takes 109.75% longer than Scenario 1, while Scenario 3 takes 278.55% longer than Scenario 1. These differences are attributed to increased geological instability and the need for additional support measures, such as reinforced concrete structures or slower excavation methods in unstable rocks. Statistical analysis of the duration per meter indicates that the standard deviation in Scenario 1 is relatively low (0.3 days/m), suggesting consistency in predictions for stable rocks. In Scenario 2 and Scenario 3, standard deviations are higher (0.7 days/m and 1.2 days/m, respectively), reflecting greater variability due to the heterogeneity of geological conditions.

Furthermore, a comparison with initial estimates from the project documentation for the Pan-European Corridor VIII shows that the duration in Scenario 1 aligns closely with planned values, while in

Scenario 2 and Scenario 3, the actual duration significantly exceeds estimates due to unforeseen geological challenges, such as local collapses or the need for additional stabilization. These findings highlight the importance of detailed geotechnical analysis prior to construction to minimize deviations from the plan. The results provide a foundation for future tunnel project planning, particularly in regions with similar geological conditions.

5. Conclusion

This paper presents an analysis of the construction time of 124 tunnel segments that are part of the Pan-European Railway Corridor VIII in the Republic of North Macedonia.

Based on the conducted analysis, it can be concluded that the type of material in which the tunnel is to be constructed has a significant impact on its total construction time. The presented results show that tunnels to be built in stable rock formations have the shortest construction time compared to the other two scenarios. This is also illustrated in the graphical representations in Fig. 2 and Fig. 3.

Fig. 2 presents the average construction duration per meter, where the value for Scenario 1 is 1.9 days/meter, for Scenario 2 it is 4.3 days/meter, and for Scenario 3 the value is 7.9 days/meter.

Fig. 3 shows the total construction duration of the tunnels for all three scenarios. The average value for Scenario 1 is 359 days, for Scenario 2 it is 753 days, while for Scenario 3, the total construction duration of the tunnels is 1359 days.

If a percentage comparison is made based on these results, Scenario 2 lasts 109.75% longer than Scenario 1, and Scenario 3 is approximately 278.55% longer than Scenario 1.

Through the scenarios presented in this paper, the analysis enables accurate planning, precise scheduling, and effective resource management.

If 21st-century technologies (such as software and modeling tools) are integrated into this analysis, the complexity of tunnel engineering challenges could be significantly reduced.

Furthermore, this analysis can also be useful in the planning of tunnels where delays in deadlines could have negative consequences on the overall tunnel construction process.

5.1. Limitations of the Analysis

This analysis assumes that an entire tunnel consists of a single rock type in each scenario, simplifying real-world conditions where tunnels typically traverse varied rock types. This assumption may affect the accuracy of predictions, particularly for tunnels with heterogeneous geology. Additionally, construction duration is influenced by factors such as the experience of construction crews, availability of mechanical equipment, and specific excavation methods (e.g., blasting versus mechanical excavation), which were not fully considered due to data limitations. Future research should incorporate detailed data on these variables to enhance result applicability.

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