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THE IMPACT OF DISCONTINUITY ON THE STABILITY OF TUNNEL EXCAVATION IN KARST

Aleksandar Golijanin[1], Bojana Grujić[2*], Jovana Munjiza[1], Žarko Grujić[2]

[1] University of Banja Luka, Faculty of Mining, Prijedor, Republic of Srpska, B&H
[2] University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy, Department of Civil Engineering, Banja Luka, Republic of Srpska, B&H

[*] Corresponding author: bojana.grujic@aggf.unibl.org

Abstract: The position of primary and secondary (stratification surfaces and fractures) discontinuities in relation to the tunnel route significantly affects the stability of the tunnel excavation. Primary discontinuities represent interlayer surfaces or stratification surfaces that formed during the period of rock formation itself, while secondary discontinuities represent fractures, i.e., discontinuities that formed after the sedimentation process was completed and are associated with tectonic activities. In addition to existing discontinuities, groundwater can also affect the stability of the tunnel excavation.

Keywords: stability, fracture discontinuity, groundwater, interlayer surface.

1. INTRODUCTION

The hydroelectric project "Upper Horizons" is based on the multipurpose use of water, which is temporarily accumulated in the middle and upper levels of karst fields in eastern Herzegovina, serving as the primary resource in this region. These waters, accumulated in the karst fields during periods of heavy rainfall, belong to the watersheds of the Buna, Bregava, and Trebišnjica rivers. Extensive research has led to the conclusion that the entire area must be treated as a single water management unit, as this is the only way to ensure the maximum benefits of multipurpose water use. In order for the entire area to truly function as a unified system, it was necessary to connect it with a network of canals along the karst fields and a system of tunnels that would interconnect the karst fields, forming reservoirs from which water could be controlled and used for various purposes. This grand hydroelectric project was initiated in the 1960s and its construction is still ongoing today.

During the implementation of this project, extensive geological, engineering-geological, geotechnical, hydrogeological, and geophysical investigations were carried out, both in the design phase and during the construction of specific tunnels. The karst terrains of eastern Herzegovina are characterized by a wide variety of karst formations, both on the surface and within the rock mass itself, due to their development.

It is important to emphasize that more than 50 kilometers of tunnels have been fully constructed within this system, making it, from a research perspective, an ideal testing ground for identifying all the specific challenges of tunnel construction in karst terrain. This study synthesizes the experiences gained from previous practice, and as such, they can be confidently applied in the completion of this grand project [1].

2. RESEARCH METHODOLOGY

During the field investigations for the construction of specific hydrotechnical tunnels, the most advanced methods available at the time were applied, both in the field and under laboratory conditions. It is important to emphasize that both the research and construction activities related to this project have been ongoing for more than 60 years. Based on the applied investigations and the obtained results, a synthesis was carried out, through which the influences of existing discontinuities—whether of primary or secondary origin—on tunnel construction in karst terrain were determined.

During the design phase, detailed geological and subsequently engineering-geological mapping of the terrain was conducted. Based on this mapping, numerous exploratory works were located—both during the design phase and additionally during the construction phase of certain tunnels. Extensive hydrogeological investigations were carried out to define the movement of groundwater between three hypsometrically different levels of karst fields.

Based on the engineering-geological mapping, the locations of a large number of exploratory boreholes, trial pits, and investigation shafts were determined. Certain geophysical investigations were also conducted, along with a significant number of laboratory geomechanical, mineralogical, and petrological tests. Additionally, a series of engineering-geological and hydrogeological maps were produced for specific parts of the terrain, depending on the construction challenges of individual tunnels and other key structures that have been or will be built (dams, canals, powerhouses, etc.), all with the aim of defining the geotechnical conditions for the construction of these structures.

Based on a large number of exploratory boreholes, the karstification zone in the area of Eastern Herzegovina was defined. The use of geobombs and dye tracing of springs helped determine the directions of groundwater flow. During the 1970s and 1980s, extensive regional geological investigations were carried out, culminating in the geological maps of Trebinje, Gacko, and Nevesinje, OGK SFRY [2, 3, 4]. These studies resolved uncertainties regarding the age of certain lithological formations, their position within the geological column, and significantly contributed to defining the physical and mechanical properties of specific formations.

3. GEOLOGICAL COMPOSITION AND HYDROGEOLOGICAL PROPERTIES OF THE TERRAIN

From the perspective of constructing hydraulic tunnels in the karst of eastern Herzegovina, it is essential to understand not only the geological composition of the terrain but also its hydrological, hydrogeological, and tectonic properties. These factors significantly influence the stability of tunnel excavation and have also played a major role in the formation of underground karst morphological features (pits, caverns, shafts, etc.).

3.1. Lithostratigraphic composition of the terrain

The region of eastern Herzegovina is part of the extensive Mesozoic-Tertiary complex of the external Dinarides. Lithologically, it is a uniform and exclusively sedimentary complex that possesses all the geological characteristics of the external Dinarides. For the purposes of this study, the lithological formations through which previously constructed tunnels have passed will be considered, as well as those through which new tunnels are planned. The most significant in this regard are the limestones of the Upper Cretaceous, specifically from the Turonian and Senonian stages (K_2^2 i K_2^3) [3].

The sediments of the Turonian stage (K_2^2) are represented by a formation of limestones with dolomites, followed by laminated dolomites with interlayers of limestone. The sediments of the Senonian stage (K_2^3) are represented by marl-rich limestones, as well as a facies of dolomites and crystalline limestones. These sediments form the rock masses through which the tunnel between Dabar and Fatnička fields (3,218 meters) was constructed, as well as the tunnel connecting Fatnička field and the Bileća reservoir (15,656 meters). Karst fields, which are distributed at three altitudinal levels, are covered by Quaternary sediments.

3.2. Hydrogeological properties of the terrain

The hydrogeological specificities of the karst terrain in eastern Herzegovina are a result of the chemical dissolution of carbonate rocks over a long geological history. Water, through its chemical composition, dissolves the surrounding limestone rocks, carrying the solution along major faults, fractures, and fissures. On one hand, when the transport capacity of these underground flows decreases, the dissolved substances precipitate, on the other. In the first phase, large erosional forms such as caverns, pits, shafts, etc., are formed, while in the second phase, accumulation forms like stalactites, stalagmites, etc., are created. This chemical action of water in limestone rocks is the process of karstification, and it is crucial to understand this process from both the design and construction perspectives when building tunnels in these areas. In the region of eastern Herzegovina, from a hydrogeological standpoint, the rock mass can be divided into two groups [5]:

- Well-permeable rocks (in which the process of karstification occurs intensively)
- Poorly-permeable rocks

The first group of rocks forms the majority of the terrain in eastern Herzegovina. These are mainly well-karstified limestones from the Turonian and Senonian stages of the Upper Cretaceous (K_2^2 and K_2^3).

In these formations, privileged pathways for the circulation of groundwater have been established, and through their chemical action, they create the previously mentioned underground erosional and accumulative features. The depth to which the rock is affected by karst processes, or the depth of karstification, varies. According to detailed studies conducted on 140 boreholes drilled in the area of eastern Herzegovina, the majority of caverns, which represent one of the main challenges encountered during tunnel construction, are found at depths between 50 and 150 meters below the surface. These investigations have also determined that the deepest cavern is located at a depth of 275 meters [5].

Poorly-permeable rocks represent the formation whose hydrogeological role can vary from a relative barrier to nearly impermeable rocks. One such formation is represented by dolomites, also a carbonate rock, which are susceptible to a specific type of disintegration (grusification). Due to their specific position within the structure of the rock mass (folds), they serve as a classic hydrogeological isolator, i.e., an impermeable layer. By recognizing this specificity of the dolomitic formation, as well as its position within the fold structure, the Bileća reservoir was created, one of the largest reservoirs in the world formed in a karst landscape.

3.2.1. Depth of Karstification

The depth to which the rocks, limestones, dolomitic limestones, and dolomites, are soluble in the area of eastern Herzegovina varies within a wide range. It is not possible to define a clear boundary between karstified and non-karstified rock masses. This is a transitional zone that can be approximated by the surface below which distinctly karstified rocks are not expected. This is known as the karstification base. Based on numerous studies conducted in this area and through the synthesis of their results, it has been concluded that the karstification base lies at a depth of 250 to 300 meters. The depth of the karstification base also depends on the fracturing and faulting of the rock mass and is deepest in areas of regional faults.

The analysis of the change in karstification and permeability with depth across the terrain was conducted for nearly the entire area of eastern Herzegovina. This analysis is based on the results of drilling and permeability tests from over 140 boreholes in areas with elevations ranging from 200 to 1,000 meters [5]. The results of these studies are presented in the diagram (Figure X), showing a general pattern of how karstification changes with depth. The diagram clearly indicates that the rock mass is most intensively karstified and has the highest porosity from the surface to approximately 20 meters. This zone is referred to as the epikarst.

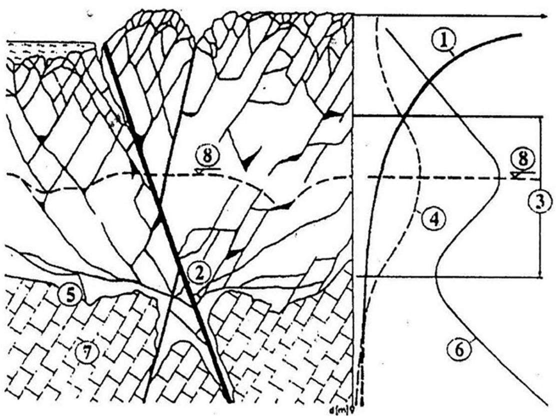


Figure 1. *Depth of Karstification, Schematic Representation (P. Milanović)*

1. Change in degree of karstification with depth, 2. Zone with base flows, 3. Groundwater level fluctuation zone, 4. Diagram of vertical distribution of active karst porosity, 5. Base of karstification, 6. Electrical sounding diagram, 7. Unkarstified rock, 8. Groundwater level.

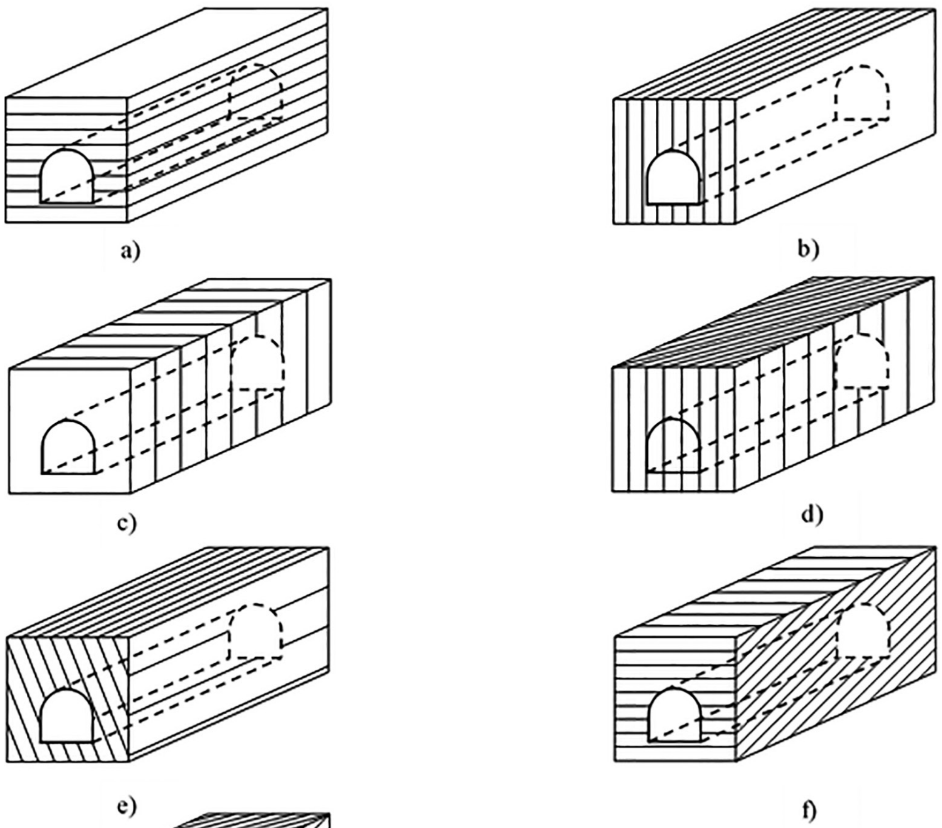
4. THE IMPACT OF DISCONTINUITIES ON TUNNEL EXCAVATION STABILITY

4.1. The impact of layering on excavation stability

Layering, or interlayer surfaces, represents primary discontinuities in the rock mass, which formed during the creation of the rock itself. Interlayer surfaces in limestones are often filled with red clay or, at times, with detrital material. The position of the layers, the way they spatially dip, and their relationship to the tunnel axis, as well as the thickness of the layers, their lithological composition, and the characteristics of the interlayer surfaces, can significantly affect the stability of tunnel excavation, as well as the occurrence of major collapses or breakthroughs. The layering of the rock mass, or the position of the interlayer surfaces, should play a significant role in the tunnel route design [6].

The most unfavorable impact on tunnel excavation stability comes from layers whose orientation aligns with the tunnel axis, while the most favorable situation occurs when the tunnel axis is perpendicular to the direction of the layers. In addition to the spatial orientation of the layers, their thickness also plays a significant role. Thicker layers provide greater stability for tunnel excavation compared to thinly layered rocks.

If the layers have a direction of strike parallel to the tunnel axis, and their dip angle ranges from 45° to 90°, this relationship is considered very unfavorable for tunnel construction. The same applies when the layers dip in the opposite direction to the tunnel's progression at an angle of 20° to 45°.



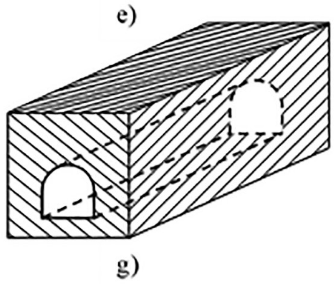


Figure 2. *Different Positions of Tunnels in Layered Rock Masses (Jevremović, Golijanin, 2025, p. 466)*
a) Horizontal Layering, b) Vertical Layering Parallel to the Tunnel Axis, c) Vertical Layering Perpendicular to the Tunnel Axis, d) Vertical Layering Diagonal to the Tunnel Axis, e) Inclined Layering Parallel to the Tunnel Axis, f) Inclined Layering Perpendicular to the Tunnel Axis, g) Inclined Layering Diagonal to the Tunnel Axis

Horizontal and subhorizontal layers are also unfavorable from the perspective of stability, especially if they are thin or foliated layers.

A particular disadvantage arises from interlayer surfaces filled with soft red clay, which facilitates the shearing of rock blocks.

The most favorable relationship between the orientation of the layers and the tunnel axis occurs when the layers dip in the direction of tunnel progression at an angle of 45° to 90°.

4.2. The impact of rock mass fracturing on excavation stability

The practice of constructing underground structures indicates that in solid rock masses, excavation stability primarily depends on the presence of cracks and other ruptures, as well as their properties. Although the strength of the rock itself is exceptionally high, instability often occurs on a local or broader scale as a result of weakened surfaces within the rock mass. The size of unstable blocks is directly related to the size of the fractures. For block movement to be possible, and for instability to occur in the rock mass within the excavation zone, the following conditions must be met:

– There must be a kinematic possibility for the block to move towards the excavation.

– The resistance properties along the fracture surfaces that limit the unstable blocks must be low enough to allow for fracturing to occur.

Fracturing in limestone rocks has its own specificities. Almost always, one family of fractures can be observed, which is perpendicular to the strike of the layers. If, in addition to this family of fractures, another one appears, and the rock mass is layered, instability inevitably occurs in such an environment during tunnel excavation. In the limestones of eastern Herzegovina, intensive fracturing is associated with regional fault ruptures and the crests or floors of folded structures. Instabilities in tunnel excavations are often related to deep faults that intersect the tunnel route. Wide fault and fracture zones are filled with debris and clayey material, significantly complicating and slowing down the progress of tunnel excavation, even when appropriate stabilization measures are applied [1].

The crests of anticline forms, or the floors of syncline forms, due to intense and strong folding processes, are heavily fractured, so the stability of the tunnel excavation that intersects these zones is significantly compromised.

During detailed engineering-geological mapping of the tunnel excavation, at locations where the tunnel route crosses the crests of anticline or the floors of syncline forms, significant fracturing or, more accurately, rock mass crushing was observed.

4.3. Analysis of rock mass stability in tunnel excavation

In the process of analyzing the stability of potentially unstable blocks around the tunnel excavation, the following phases can be identified:

- Development of Geological Input Parameters and Preliminary Assessment of Potentially Unstable Blocks
- Adoption of a Geotechnical Model with Determination of the Geometric Characteristics of Unstable Blocks, Fracture Mechanisms, and Direction of Movement
- Identification of Active Forces Acting on the Unstable Block with Given Dimensions and Shape, Determination of Failure Criteria and the Limit Equilibrium of the Blocks with the Calculation of the Safety Factor

The final result of the block stability analysis around the tunnel excavation should be a geotechnical model with identified quasi-homogeneous zones in terms of stability and failure mechanisms, along with the associated safety factor and the technical solutions required to maintain excavation stability.

The stability analysis of individual blocks can be easily and quickly performed using the positional sphere. The application of this method is illustrated in Figure 3 [1].

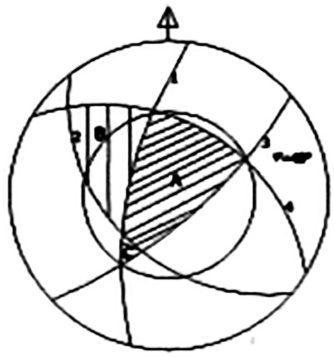


Figure 3. *Assessment of the Stability of Potentially Unstable Blocks, A – Possibility of gravitational block failure, B and C – Possibility of block movement by sliding [1]*

In the diagram representing the horizontal projection of the positional sphere, four families of fractures are shown along the routes, which are present at the location of an underground structure. The predicted angle of internal friction is $\varphi = 40°$.

The vertical line passing through the apex of the wedge in the diagram is represented by the center of the circle. If the center is within the surfaces that limit the fracture routes, then it is possible for the block to undergo gravitational failure without sliding along any of the fracture surfaces (Zone A). However, if the center of the circle is outside these surfaces (Zones B and C), then block movement in the form of sliding along one or two fracture surfaces is possible. As an additional condition for the possibility of block movement in the form of sliding, the angle of internal friction (the small circle within the larger one in the figure) is introduced. For block sliding to occur, the surface or intersecting line along which the movement takes place must be steeper than the angle of internal friction. This condition is satisfied if at least part of the intersected surface falls within the small circle, which represents the angle of internal friction.

A similar procedure can be applied to analyze the possibility of block failure from the tunnel sides, with the difference that in these cases, there is no gravitational failure as in the tunnel crown. Instead, the movement of blocks occurs by sliding along one of the fracture surfaces or along the intersection line of two fractures.

The stress state in the rocks arises as a result of forces from various origins (gravitational, tectonic, thermal, etc.) acting on the rock mass, which is typically heterogeneous in terms of composition and rock mass properties.

The greatest impact on the distribution and intensity of stresses in rock masses is caused by fractures. Depending on the properties of the fractures in the rock masses, there will be concentrations, areas with reduced stress intensity, and zones of tension.

The main properties of individual fracture families that significantly affect the stress distribution are as follows [6]:

- Spatial orientation (the angle at which the fracture intersects the direction of external forces)
- Morphology of the fracture walls
- Degree of continuity of the fractures
- Width of the fractures and deformability of the fracture filling
- Frequency of the fractures

The stress state also depends on the deformability of the monolithic part of the rock mass. Studying the impact of fracturing on the stress state of rock masses is a complex experiment and theoretical problem. As previously mentioned, the stress state depends on numerous fracture properties and all possible combinations of them. Moreover, since rock masses are typically divided into several families of varying dimensions, especially in the case of limestone formations in eastern Herzegovina, their impact on the stress state varies, making the problem much more complex.

When it comes to the karst sediments of the Turonian K_2^2 and Senonian K_2^3 stages in eastern Herzegovina, it should be emphasized that a significant role in influencing the stress state is played by the large amounts of water that infiltrate into the interior. Along all these fractures and cracks, through their chemical and mechanical actions, the water alters the stress state pattern [7].

5. IMPACT OF GROUNDWATER ON TUNNEL EXCAVATION STABILITY

Groundwater that appears or seeps into a tunnel excavation can be divided into two groups. The first group consists of infiltrating waters that appear during rainy periods. During this time, surface water seeps into the tunnel excavation along various cracks, channels, fractures, and caverns. If the rainfall is substantial, the water inflow into the tunnel excavation is also considerable. However, these waters, although they bring certain amounts of clayey-silty material into the tunnel excavation, do not significantly affect the stability of the tunnel excavation directly.

The second group consists of permanent groundwater, which is associated with large underground chambers and caverns, where the groundwater is stored. Their replenishment originates from surface water. If such channels are intercepted, water can flood into the tunnel excavation, which can be very dangerous both for personnel and machinery, as well as for the stability of the tunnel excavation itself. All karst channels may be subjected to high pressure from groundwater, the destructive effect of turbulent flow, and extremely large water inflows.

The situation can be particularly unfavorable if part of the tunnel route with caverns is located in a zone of rapid water exchange, where the groundwater level occasionally rises above the tunnel level. In such cases, the channels and caverns come under pressure and are exposed to the destructive effects of turbulent flow from large volumes of water.

Additionally, sudden fluctuations in groundwater levels can significantly affect the stability of the excavation. During rainy periods, these fluctuations can be as much as 70 meters within 24 hours, as the tunnel itself channels large quantities of groundwater toward it [8].

It is particularly dangerous when an active drainage system becomes connected to inactive or partially or fully clogged drainage channels through the tunnel. The result of this connection is the reactivation of old drainage systems and the introduction of new quantities of groundwater into the tunnel excavation. The drainage effect of the tunnel worsens the excavation conditions, especially if the tunnel bore intersects active drainage channels [9].

At locations where active drainage channels or higher concentrations of groundwater are expected, pre-drilling or horizontal drilling is recommended to determine the presence of groundwater and to facilitate its easier drainage.

All the previously mentioned effects and problems that groundwater can cause in tunnel excavation can be referred to as the immediate effects of groundwater on the stability of the tunnel excavation. There are also delayed effects, where groundwater, through its prolonged action and the chemical breakdown of limestone rocks, constantly enlarges existing fissures, channels, and cracks. The shaping of fissure surfaces, as well as the deposition of clayey material in the fissure interspaces (usually oily red clay), significantly affects the shear characteristics of the rock blocks in the tunnel excavation.

6. DISCUSSION

The studied area is predominantly composed of Upper Cretaceous limestones, from the Turonian and Senonian stages (K22 and K23). These sediments are thinly bedded, with frequent interlayers of dolomite. The layers are separated by primary discontinuities, i.e., interlayer surfaces. Regarding the fracturing of the rock masses, it is typical in the limestones that there are always at least two families of fractures, mutually perpendicular to each other. One family of fractures is always developed perpendicular to the bedding surfaces. The relationship between the discontinuities and their orientation relative to the tunnel axis affects the stability of the excavation.

In the cores of anticline structures and the bottoms of syncline structures, due to the folding process, there is increased fracturing, which significantly impacts the stability of the excavation. The spatial orientation of the fractures, the morphology of their walls, the distance between the fracture walls, the filling of the space with rubble and clayey material, as well as the continuity and frequency of the fractures, all influence the stability of the tunnel excavation.

Interlayer surfaces, as well as the existing fracture families, represent predisposed directions for groundwater flow, and thus also contribute to the chemical disintegration of the limestone sediments. As a result of the chemical disintegration of the limestone rocks, underground karst morphological forms are created. Extensive exploratory drilling has established the depth of karstification, which ranges from 250 to 300 meters.

The area under observation and investigation experiences a large amount of precipitation throughout the year, most of which infiltrates the ground and flows through underground pathways towards lower levels of the karst fields. These waters significantly affect the stability of the tunnel excavation both during construction and throughout the tunnel's operation. The geological conditions that contribute to instability during tunnel construction are found within the rock masses themselves, in the manner and conditions of their formation, as well as in their physical-mechanical properties, which reflect their ability to react more quickly or slowly to external destructive agents.

7. CONCLUSION

During tunnel construction in limestone terrains, there are many important factors that affect the stability of the tunnel excavation. The area that was the subject of this work, eastern Herzegovina, is primarily composed of layered limestones from the Turonian K_2^2 and Senonian K_2^3 stages of the Upper Cretaceous. It should be emphasized that the primary discontinuities formed during the creation of the lithological formation (interlayer surfaces), depending on their position relative to the tunnel axis and their filling with clayey material, significantly affect the stability of the tunnel excavation as well as the dynamic movements of individual blocks of the rock mass in the sides and crown of the tunnel.

In addition to the primary discontinuities, secondary discontinuities (fractures) formed as a result of tectonic movements also play an important role and are related to ruptural and plitic forms. As a rule, at least two families of fractures appear in limestone rocks, mutually perpendicular to each other.

The kinematic activity of blocks around the tunnel excavation is determined by the mutual frequency of these fractures, the size of the gaps, their filling with clayey material, etc.

In addition to the existing discontinuities, a very significant factor that affects the stability of the tunnel excavation is the presence of underground waters.

In the limestones of eastern Herzegovina, between the three levels of karst fields, a drainage network of underground channels has developed, through which primarily percolation waters, or waters of atmospheric origin, circulate. During periods of heavy rainfall, these are very large quantities of water, which, due to their force, can significantly threaten the stability of the tunnel excavation.

Underground waters located in karst springs can also pose a significant threat to the stability of the tunnel excavation if they intersect the tunnel's route.

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UTICAJ DISKONTINUITETA NA STABILNOSTI TUNELSKOG ISKOPA U KARSTU

Sažetak: Položaj primarnih i sekundarnih (površine slojevitosti i pukotine) diskontinuiteta u odnosu na tunelsku trasu, u značajnoj mjeri utiču na stabilnost tunelskog iskopa. Primarne diskontinuitete predstavljaju međuslojne površine ili površine slojevitosti, koje su nastale u periodu stvaranja samih stijena, dok sekundarne diskontinuitete predstavljaju pukotine, tj. diskontinuiteti nastali u periodu nakon završetka sedimentacije i vezani su za tektonske aktivnosti.Takođe, tokom miniranja, po obodu tunelske cijevi mogu nastati pukotine koje u značajnoj mjeri utiču na stabilnost iskopa. Pored postojećih diskontinuiteta, i podzemne vode mogu uticati na stabilnost tunelskog iskopa.

Ključne riječi: stabilnost, pukotina, diskontinuitet, podzemne vode, međuslojna površina.

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