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Research Article

Evaluation of Static and Dynamic Slope Stability with Rock Bolt Reinforcement: İzmir State Road Case Study

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Abstract - This study investigates a proposed remediation method for a rock slope located along a state highway in İzmir, Turkey. Preliminary assessment and detailed investigations within the research area revealed a potential for slope failure, particularly along the section adjacent to an underground storage tank, posing significant risks to roadway safety and infrastructure. Geological characterization and laboratory testing were conducted to determine the mechanical and shear properties of the rock units, providing essential input for subsequent stability analyses. A kinematic analysis was performed to evaluate the influence of bedding planes, joint sets, and discontinuity orientations on the overall stability of the slope. The analysis identified potential failure mechanisms, including wedge formation and toppling of rock blocks, which are primarily controlled by the geometry and spacing of the existing discontinuities. To further quantify slope behavior, a detailed slope stability assessment was carried out using both static and dynamic loading conditions to simulate natural and seismic forces, enabling the identification of critical failure surfaces and the most vulnerable zones. Subsequently, the Limit Equilibrium Method (LEM) was applied to model the reinforced slope and to evaluate various stabilization strategies. The analyses demonstrated that the implementation of fully grouted rock bolts effectively increases slope stability by enhancing shear resistance along potential failure planes and providing confinement to unstable blocks. The results of this study provide a systematic and evidence-based approach to designing reinforcement measures, contributing to the safe and sustainable maintenance of critical transportation infrastructure.

Key Words - Slope stability, static and dynamic loading, rock bolt, limit equilibrium method

1. Introduction

The assessment of highway embankments is necessary to ensure the safety of excavations such as road cut slope, mine sites, and railway tunnels, as well as to evaluate the stability of slopes. This is particularly important in steep and mountainous areas, where rock slopes pose a significant risk in road construction. Advances in computer technology have led to increased interest in using different methods for slope analysis. Moreover, several methods such as finite element method, limit equilibrium approaches have been developed in engineering to assess and design slopes in both soil mechanics and rock mechanics. Limit equilibrium analyses were used to compute the total failure analysis, the factor of safety, and the failure surface. To measure slope stability and establish the safety factor, several methodologies, including the LEM methodology, were applied. However, it is critical to understand the benefits and drawbacks of each technique. The LEM approach includes segmenting the soil/rock mass above the slip surface into a defined number of slices that can be vertically or horizontally split. Numerical methods and limit equilibrium methods have grown in importance in actual geotechnical engineering over the past several decades, and as such have become an essential instrument in civil engineering design (Tuskan, 2025)

Numerous studies have been conducted to investigate the stability of rock slopes considering the complex nature of rock masses, including discontinuities, anisotropy, and varying geological conditions (Hoek and Bray 1981; Wyllie and Mah 2004; Biswas et al. 2017; Deng et al. 2018). Traditional limit equilibrium methods, such as those proposed by Janbu, Bishop, and Spencer, have been widely applied to rock slope stability analysis by incorporating rock mass strength parameters derived from criteria such as Hoek–Brown. Greenwood (1990) extended conventional force equilibrium approaches by accounting for reinforcement effects in slope stability calculations. Subsequently, Sabhahit et al. (1994) modified Janbu's method to better represent reinforced slopes. In the context of rock engineering, various reinforcement systems—including rock bolts, anchors, and cable bolts—have been introduced to enhance slope stability by increasing shear resistance and controlling block movement along discontinuities (Hoek et al. 1995; Brady and Brown 2006). In addition to analytical methods, numerical approaches such as the finite element method (FEM), finite difference method (FDM), and discrete element method (DEM) have been increasingly employed to capture the behavior of jointed rock masses and the interaction between rock slopes and reinforcement systems (Jing and Hudson 2002; Stead et al. 2006). More recent studies have focused on probabilistic analyses, reliability-based design, and advanced monitoring techniques to better assess the performance and safety of reinforced rock slopes under static and dynamic loading conditions (Zewdu 2020; Naghipour et al. 2020). Additionally, the stability of rock slopes reinforced with rock bolts was investigated, recognizing their effectiveness in improving the mechanical behavior of jointed rock masses and controlling block instability (Hoek and Bray 1981; Wyllie and Mah 2004). Rock bolts enhance slope stability by increasing shear resistance along discontinuities, restricting block movement, and promoting the self-supporting capacity of the rock mass (Hoek et al. 1995; Brady and Brown 2006). Early analytical approaches incorporated rock bolt forces into limit equilibrium frameworks to evaluate safety factors of reinforced slopes, while subsequent studies refined these methods to better represent bolt–rock interaction mechanisms and load transfer behavior. With advances in computational techniques, numerical modeling methods such as the finite element method (FEM), finite difference method (FDM), and discrete element method (DEM) have been widely employed to simulate rock bolt–reinforced slopes, allowing for detailed analysis of bolt length, spacing, inclination, and pretension effects on slope stability (Jing and Hudson 2002; Stead et al. 2006; Biswas et al. 2017). More recent research has focused on the performance of rock bolts under complex loading conditions, including seismic excitation, weathering, and time-dependent degradation, as well as on probabilistic and reliability-based approaches to optimize bolt design and assess failure risk in reinforced rock slopes (Deng et al. 2018; Zewdu 2020; Naghipour et al. 2020).

Due to its effectiveness and affordability, the use of fully grouted bolts for reinforcing rock masses is widely employed in civil engineering to control deformation and ensure stability of engineering projects. As a result of its significance, the stability analysis of both unreinforced and reinforced jointed rock slopes has garnered considerable interest from researchers, leading to the development of numerous methods throughout the years (Baghbanan et al., 2017; Kolapo et al., 2022; Rahim et al., 2022). Furthermore, in order to ensure the safety of the storage tank located on the crest of rock slope, it is important to investigate potential geological hazards, such as sliding and rockfall incidents that have occurred in the area before. A Slide 6.020 model was used in this investigation to simulate the slope stability analysis. Therefore, this study examined how the magnitude of the surcharge load and its distance from the slope crest influence the behavior of a reinforced slope. The numerical model was developed using a slope of a specified height with moderately weathered rock characteristics.

2. Materials and Methods

The study area was located on the right side of the highway where the soil profile in the excavation section consists of Neogene aged andesitic tuff and agglomerate rocks. In order to determine the physical and mechanical properties of the units that form the foundation soils of the overpass bridge, the lithological and geotechnical characteristics of the units were examined in this section based on the data obtained. The observed Çukurköy volcanics (Tmdç) in the project area consist of andesitic tuff and agglomerate levels, while the material in the matrix position in the agglomerate levels consists of tuff rocks. This material with weak mechanical properties plays a decisive role in the behavior characteristics of the rock mass. The unit, which shows partly mechanical weathering and partly different weathering levels developed parallel to paleotectonic movements, has fractured zones in some places and generally exhibits a very closely jointed and fragmented structure, representing levels where it has completely weathered and leached to soil near tectonic linear features. In this context, the geomechanical properties determined for different weathering levels (Tmdç1 and Tmdç2) within the unit based on the data obtained from the geological-geotechnical research studies are given below. In the upper levels, fill material is observed in shallow thickness. Moderately weathered Çukurköy volcanics (Tmdç1) unit consists of andesitic tuff and agglomerate levels, and according to the foundation drilling and field observations, it exhibits a very closely jointed and fragmented structure. In the foundation research drilling, these levels were observed to be gray, light gray, brown, and yellow in color, with moderate weak to occasionally moderate strength. In addition, it was observed that joint surfaces are rough and partially filled with clay. Similarly, the excavation section envisaged in moderately-heavily weathered Çukurköy Volcanics (Tmdç2) section of the project area will be created within the andesitic tuff and agglomerate levels, and moderately-heavily weathered levels of approximately 8.00 meters thickness are observed in the upper levels of the unit, according to the foundation drilling and field observations. It exhibits a very closely jointed and fragmented structure. In addition, it was observed that joint surfaces are rough and partially filled with clay.

The numerical model of the rock slope was developed using a Limit Equilibrium Method (LEM) framework to evaluate the stability and performance of the rock bolt reinforcement under various loading conditions. The Limit Equilibrium Method (LEM) is a widely used approach for analyzing the stability of slopes (Zheng et al., 2022; Tesfaye et al., 2023). This method utilizes the principle of equilibrium to determine the safety factor of a slope, which is a measure of its stability against failure. When using the LEM for slope stability analysis with rock bolts, there are several considerations that need to be taken into account. First, the geometry and characteristics of the rock bolts, such as length, spacing, and type, must be carefully determined. These parameters will have a significant impact on the stability analysis results. For the blocks that are considered unstable, the LEM calculates the critical slip surface along which failure is expected to occur. These surfaces define the potential failure zones within the slope. Rock bolts play a crucial role in stabilizing these critical slip surfaces by providing additional resistance to sliding along the surface. Stability analysis using mass parameters has evaluated potential stability problems in the excavation section (Figure 5). In this context, stability analysis has been conducted on supported and unsupported excavation models, and it is observed that the intervals between elevations of approximately 58.0 – 68.0 require support with rock bolts at 9.00 m, the intervals between elevations of approximately 68.0 – 78.0 require support with rock bolts at 12.00 m, and elevations above 78.0 can be left as a free slope with a 3/2 (h/V) slope ratio, ensuring sufficient safety numbers (Figure 1).

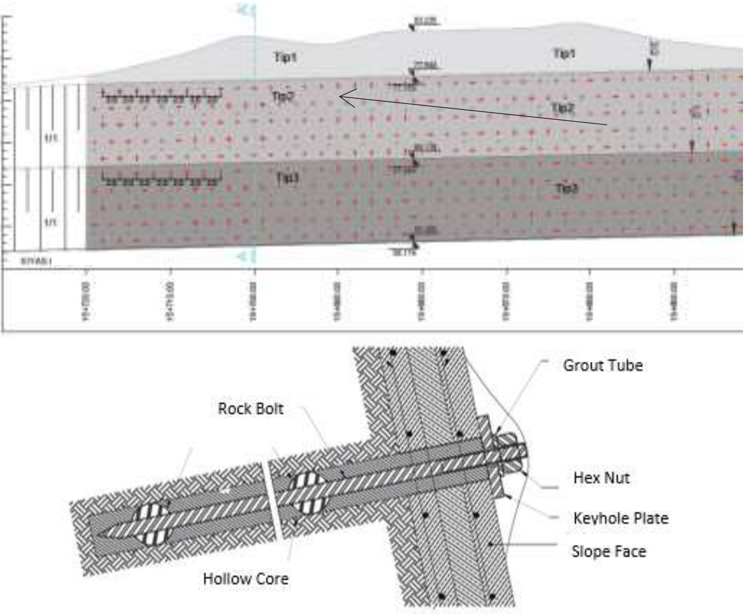


Figure 1. Rock Bolt Application on Cross Section of Rock Slope

To analyze the stability of a slope reinforced with rock bolts using the LEM, the shear strength parameters and the mobilized strength of the bolts must be properly assigned. The mobilized strength of the rock bolts can be determined through various testing and monitoring techniques. The LEM applies equilibrium equations, such as the force equilibrium and moment equilibrium, to each block in order to calculate the safety factor of the slope. The safety factor is the ratio of the resisting forces (e.g., shear strength of the rock, mobilized strength of the bolts) to the driving forces (e.g., weight of the slope, external loads). The Limit Equilibrium Method (LEM) is an effective technique for analyzing the stability of slopes with rock bolts. By considering the forces acting on the slope and the resistance provided by the bolts, this method allows engineers to assess the safety factor of the slope and design appropriate rock bolt reinforcement measures to ensure stability.

3. Results and Discussions

In this study, the soil conditions of the road cut slope have been evaluated in terms of geology and geotechnics. Then, the geomechanical properties of the units located in the proposed cut section, the application of the idealized soil profile, and the stability conditions have been assessed. The proposed cut section consists of moderately to highly weathered andesitic tuff-agglomerate rocks belonging to Çukurköy volcanics. The unit generally has a highly jointed structure, and the discontinuities cannot be clearly observed due to the degree of weathering in some tuff levels. Regarding the proposed cut section, section studies have been conducted on various slope combinations, and alternative slope protection measures have been examined in order to ensure the long-term stability of the slope and reach the most practical and economical solution. In parallel with this, in slope design studies, excavation sections with 5.00 meters wide benches and 10.00 meters high cuts have been used. The proposed slope ratios for excavation have been initially analyzed using the kinematic analysis method, and if stability problems are encountered depending on the location of the discontinuities, the slope in question has been checked through analytical analysis. In addition, the circular sliding potential has been investigated in sections where completely weathered rocks are exposed.

3.1. Kinematic and Analytical Analyses

The potential for planar and wedge-type sliding and toppling of the selected vertical excavation surface, taking into account the geomechanical properties of the units in the proposed cut section and the topographic conditions, has been examined through kinematic analysis. The discontinuities determined during geological mapping are given with their contour diagrams and stereographic projections in Figure 2. Kinematic analyses were performed using the Dips 5.107 computer program, and parameters recommended by different sources for use in kinematic analyses were evaluated, and strength parameters representing the discontinuities were selected.

As an approach, ultimate strength parameters for unfilled discontinuities are given as $Ø_u$ = 30-35° in strong and massive rocks, $Ø_u$ = 25-30° in layered or schist rocks, and $Ø_u$ = 20-25° in soft, laminated, or schist-type rocks. The joints have a rough and wavy surface, $Ø_u$ value is increased by 5-15°, while for weathered joint surfaces, this value is predicted to be reduced by 5-10°. For the andesitic tuff-agglomerate rocks observed in the study area, the discontinuity strength parameters were determined to be $Ø_u$ = 30°. In this assessment, it was assumed that residual cohesion would decrease due to factors such as rock relaxation after excavation on slope surfaces, relaxation along the discontinuities, and absence of filling on the discontinuity planes. In excavation process, vertical joints are not preferred due to their tendency to form dominant joint sets. In this context, excavation surfaces with a 2/3 (horizontal/vertical) slope were evaluated kinematically. The slope directions of the designed excavations start at 330° in the right cut section of the highway and end at 230° at the highway intersection. On the highway, it continues with 291°. The friction angle of the joints, $Ø_u$, is assumed to be 30°, and the results of the kinematic analysis are presented in Figure 2.

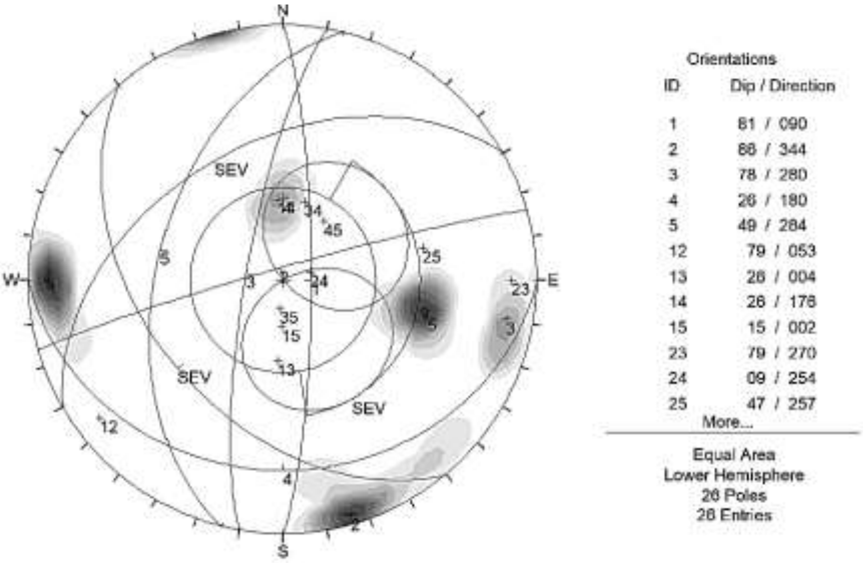


Figure 2. Kinematic Analysis of Highway Section at Km: 15+400 – 15+852

3.2. Slope Stability Analyses

Stability analyses in the static condition for the determined critical section were carried out using the SLIDE 6.005 program with the Bishop (1960) and Janbu (1973) methods. In the analyses, the type in which the stress-strain relationship can be defined for the "Tmdç1 and Tmdç2" levels was selected. For slope stability, a Factor of Safety (F.S.) value greater than 1.50 in static condition and greater than 1.050 in the earthquake condition was sought. If the desired safety numbers cannot be achieved in the unsupported slope or as a second alternative, the use of an anchored slope with bolts is envisaged. In the calculations, the maximum lateral pressure value of $fs_{max} = 125kN/m^2$ was taken for the rock bolt to be constructed in Tmdç1, and fs_{max} = 100kN/m for the rock bolt to be constructed in Tmdç2. The hole diameter for the rock bolt was taken as Db = 10.00 cm, and the safety number value to be applied to the maximum lateral pressure value was accepted as F.S. = 2.00 in the static condition and F.S. = 1.50 in the earthquake condition.

Stability analysis of supported slopes were carried out according to the procedure described below. Accordingly, the slope was analyzed while unsupported in the static condition and the critical slip circle was determined. In order to ensure slope stability, an appropriate bolt spacing was selected vertically and horizontally, the bolt lengths were adjusted to be outside of the critical slip geometry defined above in order to achieve the desired safety number for the slope, and slope stability analyses were renewed for this geometry. In the analyses, the largest acceleration value for an earthquake with a probability of occurrence of occurrence of 10% in 50 years was used as PGA = 0.450. In this context, the expected maximum horizontal ground acceleration in the project area during an earthquake is $A_{max} = 0.45$ g, and the horizontal earthquake coefficient was taken as $a_h = 0.5\ A_{max} = 0.225$ g in the slope stability analyses (FHWA,1998). For permanent slope stability, a F.S. value greater than 1.50 for shallow slip circles and greater than 1.30 for deep slip circles in the static condition, and a F.S. value greater than 1.05 in the earthquake condition was sought.

The cross-section excavation with a slope angle of 1/2 (h/V) within the Çukurköy volcanics, reaching a height of 24.77 meters at Km=15+684, has been selected as the most critical section. The analysis results are presented in Table 1. As can be seen from the safety values and analysis details presented in Table 1., the safety values of the unsupported slope in this area with a maximum height of 24.77 m are below the desired limits. Therefore, it is proposed to support the right half-section continuing at approximately maximum height in the section Km=15+600-15+720 with bolts, and the support geometry to be used in the analyses is presented in Table 2.

Table 2. Rock Bolt Reinforcement Properties

Application Area Elevation	**Rock Bolt Diameter, (mm)**	**Horizontal Spacing, (m)**	**Vertical Spacing, (m)**	**Rock Bolt Length, (m)**
58.00-68.00	26	2	2	9
68.00-78.00	26	2	2	12

The design loads adopted in the analyses to satisfy both rupture and sliding safety requirements are summarized in Table 3. These loads were determined by considering static and dynamic loading conditions in accordance with the prescribed factors of safety. Under static conditions, a factor of safety (F.S.) of 2.00 was applied, while a reduced factor of safety of 1.50 was adopted for dynamic conditions to account for seismic effects. The corresponding service load capacities of the rock bolts, calculated as a function of bolt diameter, are presented to ensure adequate structural performance under both loading scenarios.

Table 3. Rock Bolt Load Capacity

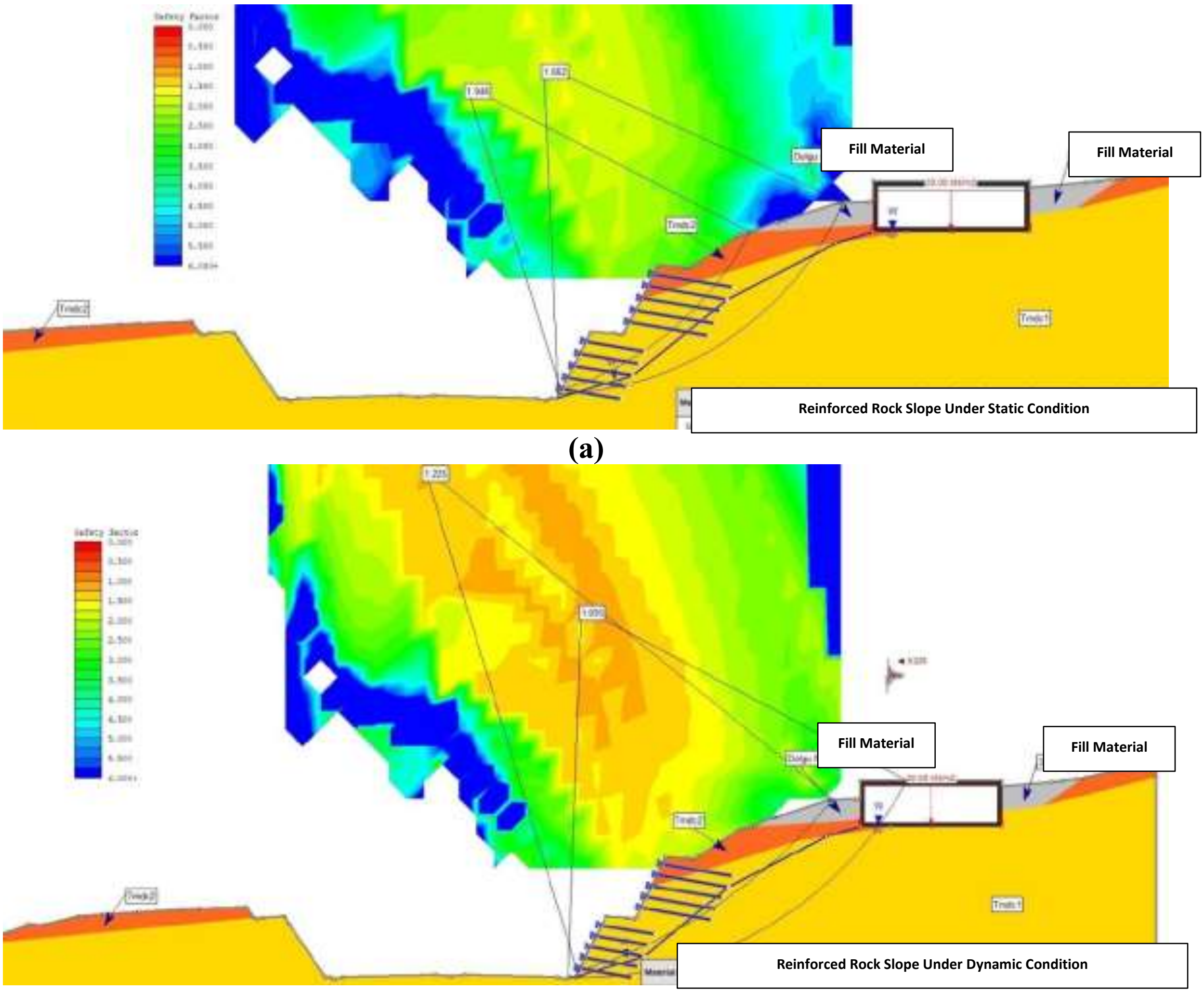
Rock Bolt Diameter, (mm)	**Service Load, kN, (Static, F.S.=2.00)**	**Service Load, kN, (Dynamic, F.S.=1.50)**
26	94	126
26	145	195

Based on the selected slope geometry and by applying the analytical procedure described at the beginning of this section, reinforced slope stability analyses were carried out. The results of these analyses are presented in Table 4, while the corresponding failure mechanisms and reinforcement configurations are illustrated in Figure 3(a) and Figure 3(b). The analyses consider both static and dynamic conditions in order to evaluate the performance of the rock-bolt-supported system under different loading environments.

Table 4. Reinforced Slope Stability Analysis with Rock Bolt

Slope Height	F.S. of Reinforced Rock Slope with Rock Bolt (Static Condition)	F.S. of Reinforced Rock Slope with Rock Bolt (Dynamic Condition)
24.77	1.662	1.095

As indicated by the analysis results, the calculated safety factors for the reinforced half-slope with a 1/2 (H/V) inclination exceed the minimum recommended values for permanent slopes under both static and dynamic conditions. In particular, the static safety factor demonstrates a satisfactory margin of stability, while the dynamic safety factor remains above the critical threshold, indicating acceptable performance during seismic loading. Therefore, no global instability or overall failure is anticipated for the reinforced slope configuration considered in this study.



(a)

(b)

Figure 3(a) Reinforced Rock Slope Stability (Static Condition) (b) Reinforced Rock Slope Stability (Dynamic Condition)

Consequently, the possibility of narrowing the excavation slopes by steepening and supporting them has been investigated, and the summary of the support systems to be implemented in accordance with the stability analysis is examined in this section. In order to ensure long-term stability in excavation slopes, it is recommended to support the half-slope excavation with a 1/2 (h/V) ratio based on stability analysis.

4. Conclusion

In the analysis of the cross-sections, the implementation of the planned rock-bolt-supported slope system was adopted in accordance with the results obtained from the stability analyses. Based on the evaluation of data derived from detailed geological and geotechnical investigations, the cross-section is composed predominantly of andesitic tuff and agglomerate rock units belonging to a volcanic formation, together with their associated bedding planes. The orientation and mechanical characteristics of these discontinuities significantly influence the stability behavior of the slope. Consequently, the construction of relatively steep excavation surfaces is required in this section to meet geometric and functional constraints, particularly in relation to the highway alignment.

Considering the unfavorable geological conditions and the necessity for steep slopes, a comprehensive slope stabilization system was designed and evaluated. For the steep excavation surfaces planned along the highway section between Km: 15+600 and Km: 15+720, horizontal drains are proposed to provide deep drainage and reduce pore water pressures within the rock mass. In addition, shotcrete will be applied to the slope surfaces to prevent weathering, raveling, and local block detachment, thereby enhancing surface stability. Head ditches will also be constructed at the crest of the slope to intercept and divert surface runoff, preventing infiltration and erosion that could adversely affect the excavation faces.

Furthermore, it is considered appropriate to install subsurface drainage systems along the excavation base throughout the cross-section to effectively control both static and dynamic groundwater conditions. This integrated drainage approach, combined with surface water management measures, is expected to significantly reduce hydrostatic pressures and improve overall slope performance under both static and seismic loading conditions. The positive influence of these drainage measures on stability is reflected in the analytical results, which demonstrate improved safety factors for the reinforced slope system.

The stability analyses conducted using the selected slope geometry and rock bolt design parameters indicate that slopes reinforced with rock bolts achieve safety factors exceeding the minimum required limits for permanent slopes. As previously presented, the reinforced half-slope with a 1/2 (H/V) inclination yields satisfactory safety factors under static conditions and maintains acceptable performance under dynamic conditions. Accordingly, the combined application of rock bolt reinforcement, drainage measures, and surface protection techniques ensures global stability and confirms that no overall failure or significant instability is expected in the analyzed cross-sections.

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