Journal of Earth & Statistics
Journal homepage: http://www.Jes.arakut.ac.ir
Doi: 10.22034/JES.2023.1999733.1029

Ministry of Science, Research & Technology
Arak University of Technology

Stability Analysis of the rock slope of the Gabric Dam spillway trench head in south of Iran

Hamid Hashemi[1], Abdollah Yazdi[1*], Ebrahim Sharifi Teshnizi[2]

[1]Department of Geology, Kahnooj Branch, Islamic Azad University, Kahnooj, Iran
[2]Department of Geology, Faculty of Science, Ferdowsi University of Mashhad, Mashhad, Iran

Article Info

Keywords:
Stability analysis, rock slope, Gabric dam, discontinuity.

*Corresponding Author's Email Address: yazdi_mt@yahoo.com

Abstract

Slope stability is one of the most important topics of engineering geology with a background of more than 300 years. So far, various stability assessment techniques have been developed which include a range of simple evaluations, planar failure, limit state criteria, limit equilibrium analysis, numerical methods, hybrid and high-order approaches which are implemented in two-dimensional (2D) and three-dimensional (3D) space. In the meantime, limit equilibrium methods due to their simplicity, short analysis time, coupled with probabilistic and statistics functions to estimate the safety factor (F.S), probable slip surface, application on different failure mechanisms, and varied geological conditions has been received special attention from researchers. Stability analysis is essential to ensure the stability of rock slopes. There are various methods for stability analysis of slopes, especially rock slopes. According to the geological studies, the considered slope which is in the spillway area of Gabric dam (south of Iran), is located in marl-sandstone layers' question, with Eocene Oligocene age. Considering the height of this terrace and the gradual process of changing the nature of the layers from marl to sandstone, the considered parameters are equivalent parameters. In the analysis of the overall stability of a rock slope, the parameters of shear strength have been used based on the Hoek-Brown failure criterion. After the analysis of the overall stability and the design of the support system, the stability of the stone wedges has been analyzed and the adequacy of the support system for the stability of the wedges that have the potential to slip. has been investigated and also to consider the loading related to the earthquake, in addition to static analyses, quasi-static analyzes have been performed by applying horizontal acceleration corresponding to the design and use level of the roof to reach the appropriate reliability coefficients. According to the analysis, it shows that in the spillway of Gabric Dam, there is a planar rupture and a pit, which reduces the reliability factor due to saturation and earthquake. The presented paper provides slope stability analysis of Spillway of Gabric dam to limit equilibrium methods used for discontinuous rock slope stability analyses with different failure mechanisms of natural and cut slopes. The article attempted to provide a slope stability of spillway of Gabric dam for rock slope stability analysis outlook based on Transfer and Kinematic analysis.

1. Introduction

The first phase of building a structure, including a trench, is designing a structure as an underground structure. As a whole, design means predicting all the issues and problems that will occur during the implementation or construction of a structure, and finally, providing a solution to overcome these problems and determine a plan for the structure in question, taking into account economic and safety aspects can to satisfy the user's demands in the desired period of time (Sadeghpour et al. 2008; Poorbehzadi et al. 2019; Karimizad et al. 2020; Asthana and Khare 2022; Grayaa and Louati 2022; Sharifi Teshnizi et al. 2022)

The design of a trench will ultimately lead to the calculation of a suitable maintenance system. The design of any structure, including a trench, requires a series of engineering information. The necessary information in the design of the spillway will be obtained from the construction of the spillway. Because the nature of information on the ground is an estimate, that means there is a possibility of error. Therefore, the more accurate the information, the more accurate the design will be (Zeidan 2015; Ozbek 2017; Arjmandzadeh et al. 2019; Sharifi Teshnizi et al. 2021b; Asfaw et al. 2022; Li et al. 2022).Therefore, designers should use different design methods, which include: experimental methods, analytical methods, and observational methods.

Each of these methods have strengths and weaknesses. It should be noted that all design analysis methods are only approximations of the real case.

Experimental methods: These methods evaluate the stability of tunnels and mines using statistical analysis. Rock engineering classification is the best known experimental methods for evaluating underground spaces and trenches in rock. In fact, in many projects, rock engineering classification is considered as the only criterion for designing complex underground structures (Davoudi et al. 2014; Sharifi Teshnizi et al. 2019; Kumar and Muthukkumaran 2022). Most of the trenches that are being built now use the classification of rocks for design. The most important of these classifications are:

- ✓ Geomechanical classification of rock mass (RMR), which was presented by Bieniawski (Bieniawski 1993; Bieniawski et al. 2017).
- ✓ Rock mass quality index (Q), which was presented by Barton et al. 1974, 1981; Barton 1978.
- ✓ Geological resistance index (GSI), which was presented by Marinos and Hoek 2000; Hoek 2002; Hoek et al. 2002.
- ✓ Rock mass index (RMi), which was presented in Palmström 1996, 2009.
- ✓ Classification of SMR was presented by Romana 1993; Romana Ruiz et al. 2001; Romana et al. 2015.

Observational methods: These methods are based on laboratory and on-site measurements. In these methods, some help is taken from experimental methods, but As a whole, the basis of analysis and engineering judgment about the implementation of the structure and maintenance system is based on instrumentation and behavior measurement of the desired structure (Liu et al. 2017; Briggs et al. 2019; Sharifi Teshnizi et al. 2021c)

Analytical methods: In these methods, the analysis of stresses and deformations around the trench is used. These methods include techniques such as closed form solutions, numerical methods and physical modeling. In recent years, in order to design deep trenches with large dimensions, more numerical analyzes have been used. Currently, the following five numerical methods are very common in solving geotechnical problems (Nassirzadeh Goorchi et al. 2019; San Mauro et al. 2019; Grayaa and Louati 2022; Kumar and Muthukkumaran 2022; Li et al. 2022)

- ✓ Finite element method (FEM)
- ✓ Finite difference method (FDM)
- ✓ Boundary element method (BEM)
- ✓ Discrete element method (DEM)
- ✓ Hybrid methods

Slopes need be designed and cut with a margin of safety for open pit mines. Economics could be improved by steepening the slope thereby reducing the amount of waste excavation; however, excessive steepening of slope could result in failure leading to loss of life and damage to property (Singh et al. 1989; Singh and Singh 1992; Singh and Goel 1999; Sharifi Teshnizi et al. 2022). The factors, which mainly influence the stability of a typical open-pit slope, are the shear strength parameters of slope forming material, the presence and characteristics of discontinuities in the slope mass and the groundwater conditions (Singh and Monjezi 2000; Singh et al. 2008; Rastegarnia et al. 2018; Arjmandzadeh et al. 2019; Karimizad et al. 2020; Sadeghi et al. 2020)

The slope stability is considered as a most extensive description for soil and rock (or combination of both) slope masses under various failures (Akgün and Koçkar 2004; Bertolini 2010; Akgun 2012; Johari et al. 2015; Johari and Lari 2016; Azarafza et al. 2017, 2021; Dahoua et al. 2018; Sharifi Teshnizi et al. 2019, 2021a; Zeqiri et al. 2019; Arjmandzadeh et al. 2019; Fredj et al. 2020).These movements can cause damages under certain conditions (Azarafza and Ghazifard 2016; Yang and Liu 2018; Raghuvanshi 2019; Yang et al. 2019; Zheng et al. 2019; Liu et al. 2020). These conditions can be classified related to geometry and geo-material status which determine the behavior and the critical slip surface expansion. Figure 1 shows various types of possible slip surfaces based on limit equilibrium analysis approaches which are directly depending on the geological conditions of the slope mass (Zhang et al. 2021). The existence of such a slip surface complicates the stability analysis and demands to consider more assumptions for covering the existing uncertainties. Therefore, the methods used in stability analysis have undergone a number of changes and improvements. In this task, the theoretical foundations and a literature review of stability analysis using the limit equilibrium method are presented herein which are successfully used for accurate description of slope failure mechanisms and stability analysis. In general, the type of slope failure directly depends on the geological units and constituent geo-materials, geometric characteristics, stress–strain history, structural and tectonic conditions, geo-morphology status, regional climate, seismic activity, water conditions (surface and underground), vegetation, weathering, drainage pattern, construction activities and special occasions (Ansari et al. 2021; Azarafza et al. 2021; Wu et al. 2021; Youssef and Pourghasemi 2021; Asfaw et al. 2022; Asthana and Khare 2022; Grayaa and Louati 2022). According to the nature of the slippery mass, it can be stated that the slope failure mode in isotropic and homogeneous masses such as soils is mostly rotational (or massive failure). If there is a rigid surface or resistant layer, they occur in planar form (Abramson et al. 2001). Depending on the discontinuity network, joint orientation, infilling material, the rock masses undergo a wide range of failures such as wedge failure, planar failure, rotational failure, and toppling failure (Hoek and Brown 2019). Most commonly, failure occurrence in slopes can be classified into the main and secondary groups. The main group consists of wedge failure, toppling failure (rock slopes), planar failure, rotational failure (rock and earth slopes) and the second group consists of composite slips, special cases, glacial slips, etc.(Skempton 1984; Abramson et al. 2001; Romana et al. 2015; Alashti 2018; Ietto et al. 2018).

Wedge failure: This failure type is one of the most common failure types in the discontinuous rock masses and it occurs based on the slip geometry in wedge form leading to tilt towards the slope face with a deviation degree less than the free face of the slope which slides along the inter-section of the discontinuities downwards the slope (Zhou and Wang 2017).

Planar failure: This failure type is also a special case of slip that occurs because of the geological conditions and the geometry of the discontinuities, where slip occurs along a surface on the main discontinuity or a layer that is more related to the geotechnical conditions from the upper mass (Wyllie and Mah 2004).

Toppling failure: Occurs in rock slopes where the discontinuity orientation with a deviation degree close to the vertex and opposite to the excavation orientation/slope faces occurs. Because of the sliding gravity geometric center positioning, the blocks are extruded along the slope driven by gravity, which is referred to as toppling (Zheng et al. 2019).

Rotational failure: This type of slope movement is observed inhomogeneous and isotropic masses such as soils, severely discontinuous, and weak rock masses. The occurrence mechanism of rotational movement is to form a shear surface that engulfs the entire mass as a curvature or circle and may involve several smaller rotational slips in the mass body (Wyllie and Mah 2004).

Also, The shear strength reduction (SSR) method was used for soil slope stability analysis in 1975 (Zienkiewicz et al. 1975). Duncan (1996) defined the factor of safety of soil slopes as the ratio of actual shear strength to the minimum shear strength required to avoid failure, or the factor by which shear strength must be reduced to bring a slope to failure. This method was applied for rock masses (Bolton Seed and Duncan 1987; Duncan 1996; Shangyi et al. 2003). Yingren and Shangyi (2004) and Hammah et al. (2007) demonstrated the efficiency of SSR method for slopes of soil and rock masses. This method was also adopted in several other studies, such as (Hammah et al. 2004; Zheng et al. 2009; Sheen et al. 2014; Gupta et al. 2016).

Therefore, every year due to the occurrence of earthquakes, many human and financial damages are caused due to the sliding of roofs in different regions of the world. The location of Iran in an earthquake-prone region of the earth on the one hand and the need to carry out various constructions in mountainous areas and in the vicinity of natural hills on the other hand, doubles the attention to the factors affecting the seismic stability of the hills. Iran is a seismic country due to its location on the Alpine earthquake belt, therefore the effect of earthquakes on stone structures in Iran is of particular importance. Among these stone structures, there are rock slopes that, due to the mountainous nature of Iran, rock slopes around the roads become significant. On the other hand, due to the existence of mineral capacities in Iran, especially in the form of surface mines, they are an important part of mineral structures. The slopes will be rocky. Also, one of the most important factors in the failure of dams is the unfavorable conditions of the foundation and the land of the dam site (Attia et al. 2021; Ribas et al. 2021; Sharifi Teshnizi et al. 2021a, b; Asfaw et al. 2022).

The objective of this paper is to slope stability of the spillway of Gabric dam of limit equilibrium-based methods for discontinuous rock slope stability analyses (i.e. wedge, planar, toppling failure) and for weak rock or soil-like lithologies (i.e. mass failure) of natural slopes as well as of cut slopes. The prepared article provides information about the limit equilibrium procedure to estimate the failure mechanisms in rock slopes. The main focuses on this matter are to provide principles and applications of stability analysis procedures especially, of the most recently developed methods named ‘Block theory’. Therefore, in this research, taking into account the geological and engineering geology conditions in the spillway area of Gabric dam in the south of Iran, the stability analysis of the spillway trench has been analyzed.

2. Materials and methods

2.1. The study area

The studied area in Hormozgan province is about 430 km southeast of Bandar Abbas and 98 km northeast of Bandarjask and in the 58´ 8″ to 58´ 48 E and 25´ 52″ to 26´ 47″ L. The access to the studied place is through asphalt Bandar Abbas-Minab-Jask-Konark road. Along this route, after crossing the Jegin river, a side road branches off to the left, which leads to Titken village. The said road to this area is dirt and grade 3 and the length of this road to the dam area is 42 km. Figure 1 shows the geographic location and access roads of the studied area.

The geomorphology of the studied area is because it is located in the catchment area of Gabric river and this area follows the geological conditions governing the area which is located in Makran area. Therefore, the highest place in the studied area is 1432 meters in the northeast of the basin, in the north of Dad Mardan village, and the lowest point is in the construction of the dam, at a height of 30 meters above the Sea level.

Based on the sedimentary and structural zone of Iran, the studied area is located in Makran structural zone. The sedimentary units in the studied area are Eocene-Oligocene, and these rock units were introduced as the Lower Flysch series by (Ghorbani and Ghorbani 2013; Ghorbani 2021). In this unit, there is a layer of pebble conglomerate to sand, dark mica sandstone with green to gray and brown shale and marl, reef limestone and sand (Figure 2).

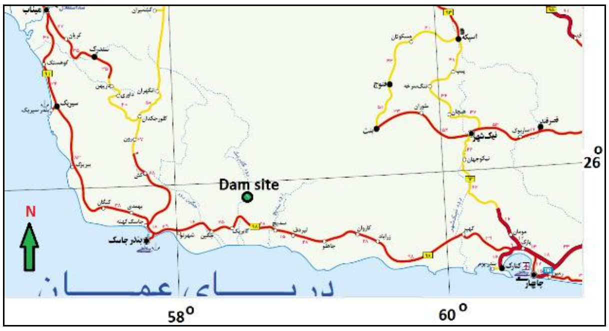

Fig 1. Schematic of access road to the studied area

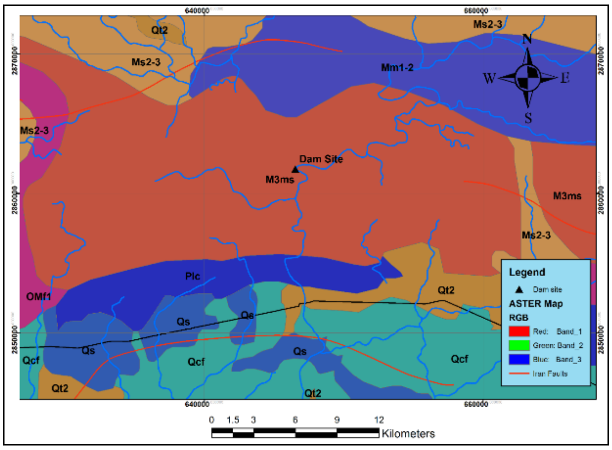

Fig 2. Geological map of the studied area

2.2. Stability analysis methods

Conventional rock slope analysis methods are generally divided into two categories: kinematics and limited equilibrium techniques. In addition, computer-based analytical methods have been developed to analyze critical rock falls (usually referred to as rock fall simulation).

2.2.1. Kinematic analysis

Kinematic methods are focused on the possibility of transition drops due to the change of the edges or the thickness of "bright day". Also, these methods are valid based on the accurate evaluation of the mass structure of the rock and the geometry of the discontinuous groups that may be involved in the instability of the rock. This participation is done by diagrams or special codes that deal with the formation of surface and edge. For example, the DIPS program visualizes and defines the kinematic feasibility of discrete features (Figure 3).

It is necessary for users to be aware that such views only detect storage spills that include single discontinuities or discontinuity joints and do not cover spills that include connections or series of connections or internal deformation and internal cracks. However, the data of discontinuity and disconnection of series connections in the DIPS program can be entered to contribute to the edge-shedding safety factor for cooperation with finite-equilibrium codes (for example, SWEDGE Rock Science B). These programs often have potential tools in which a variety of connection series features and support sizes are added, due to their effect on the safety factor.

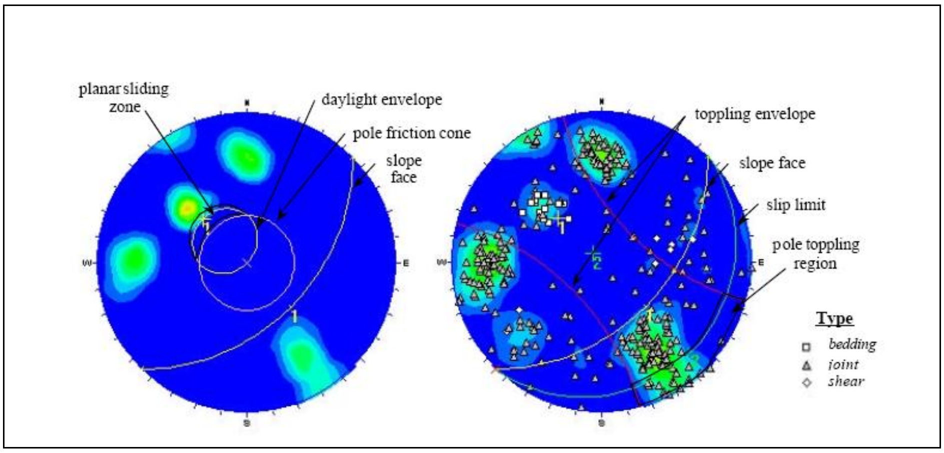

Fig 3. Feasibility measurement of surface (left) and overturning (right) kinematics and stability analysis using stereographic structures.

Analyzing the feasibility of separation can be performed on a computer based on the key block hypothesis (Goodman and Shai 1985). The stability of these key blocks is investigated using limited equilibrium methods such as the SAFE X program (Windsor and Thompson 1993) and KBSLOPE (Penteknica 2001).

Dips software is the best software to Kinematic Analysis, as Dips is designed for the interactive analysis of orientation based geological data. The program is capable of many applications and is designed for the novice or occasional user, and for the accomplished user of stereographic projection who wishes to utilize more advanced tools in the analysis of geological data. Dips allows the user to analyze and visualize structural data following the same techniques used in manual stereonets. In addition, it has many computational features, such as statistical contouring of orientation clustering, mean orientation and confidence calculation, cluster variability, and qualitative and quantitative feature attribute analysis. Dips is designed for the analysis of features related to the engineering analysis of rock structures, however, the free format of the Dips data file permits the analysis of any orientation-based data (Figure 4).

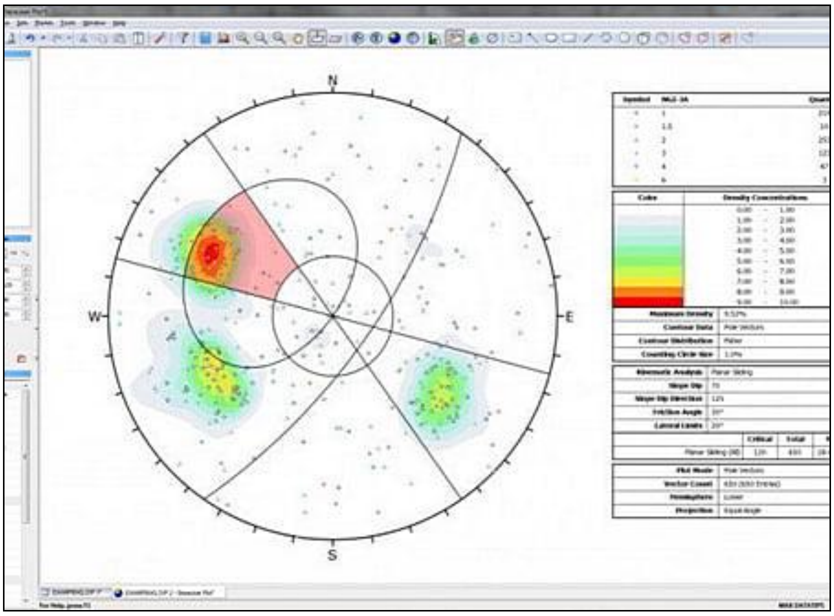

Fig 4. Calculation method of the analysis of rock slopes in the form of Dips

2.2.2. Limited equilibrium analysis

Finite equilibrium techniques are commonly used in the analysis of landslides, where translational or rotational displacements occur on separate slip surfaces. These analyzes are responsible for preparing the safety factor and a range of shear strength parameters in the flow during the inverse analysis. As a whole, these methods are the most commonly accepted solution methods in rock mechanics engineering, even though many of the spills have deformations and complex internal cracks, which have little resistance to the two-dimensional rigid block assumptions that are required by finite equilibrium analyses. However, limited equilibrium analyzes can be very relevant to simple block falls along discontinuities or rock slopes that are severely fractured or weathered. (That is, behaving like a string of soil)

All limited balance techniques have a common point of view based on the comparison of resistance forces or torque and destructive forces or torque. The methods can change according to the mechanism of the slope in question (for example, translational or rotational sliding), and the assumptions accepted to reach a specific solution. In recent years, considerable progress has been made in relation to commercially available finite-equilibrium computer codes; which include the following:

• A set of two-dimensional finite equilibrium codes with finite element groundwater flow and pressure analyzes (for example, SIGMA/W Geoslope, SEEP/W and SLOPE/W Geoslope 2000).

• Development of potential limited equilibrium techniques (eg SWEDGE - Rock Science 2001b; ROCPLANE - Rock Science 2001c).

• Development of three-dimensional limited equilibrium methods (for example, Hanger et al. 1989; Lem and Fredland 1993).

• The ability to accept support and various reinforcements.

• Incorporation of unsaturated soil shear strength standards.

• Significantly improved in terms of images and graphics before and after processing.

2.2.3. Transfer analysis

Finite equilibrium solutions and surface spills. Cracking is widely used to determine rock slope instabilities whose discontinuities are controlled. In these techniques based on the solutions introduced by Hoek and Berry (1991); is, the translational sliding of the rigid body along one plane or along the common section of two planes is assumed in the case of cracks. Since the ; The sliding block does not undergo any rotation of the rigid body, all forces pass through the center of gravity of the body ; As with all finite equilibrium solutions, it is assumed that all points along the slip plane are at the yield edge.

With these assumptions, the problem is determined statically and the calculations of the ratio of resisting forces and driving forces (i.e. safety factor) are simplified. The resisting forces are obtained from the shear force of the sliding surface (for example, adhesion and friction) and the driving forces generally include the mass component of the sliding block when it is upside down and the water pressure at the block boundaries. In Figures 5 to 6, these forces and the corresponding safety factor formulation are depicted for plate and crack stability issues. Solutions related to thickness with non-vertical tensile cracks and non-horizontal upper slope surfaces (Sharma et al. 1995), stepped slip surfaces (Quarry and Fritz 1984) and cracks with adhesive forces and water pressures (Hook and Berry 1991) are compatible with the aforementioned solutions.

Computer programs based on these solutions, such as SWEDGE (Rock Science 2001b), provide a data entry and rapid response system for evaluating the geometry and stability of surface cracks defined by two intersecting discrete surfaces and a slope plane; There are similar programs for planar analysis (such as ROCPLANE, Rock Science 2001). Another fact that computer-based solutions are useful is that they often have potential tools that can determine the variation in connection properties and rock screw support for their effect on the safety factor (Figure 7). Similarly, logic routines designed to manage ambiguities in input parameters can be accommodated.

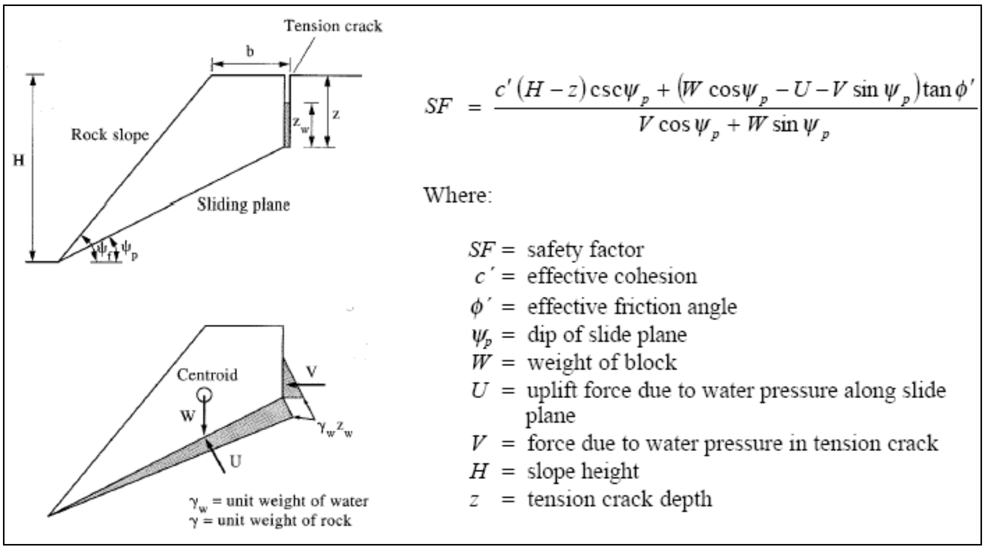

Fig 5. Calculation method of the analysis of rock slopes in the form of planar slide

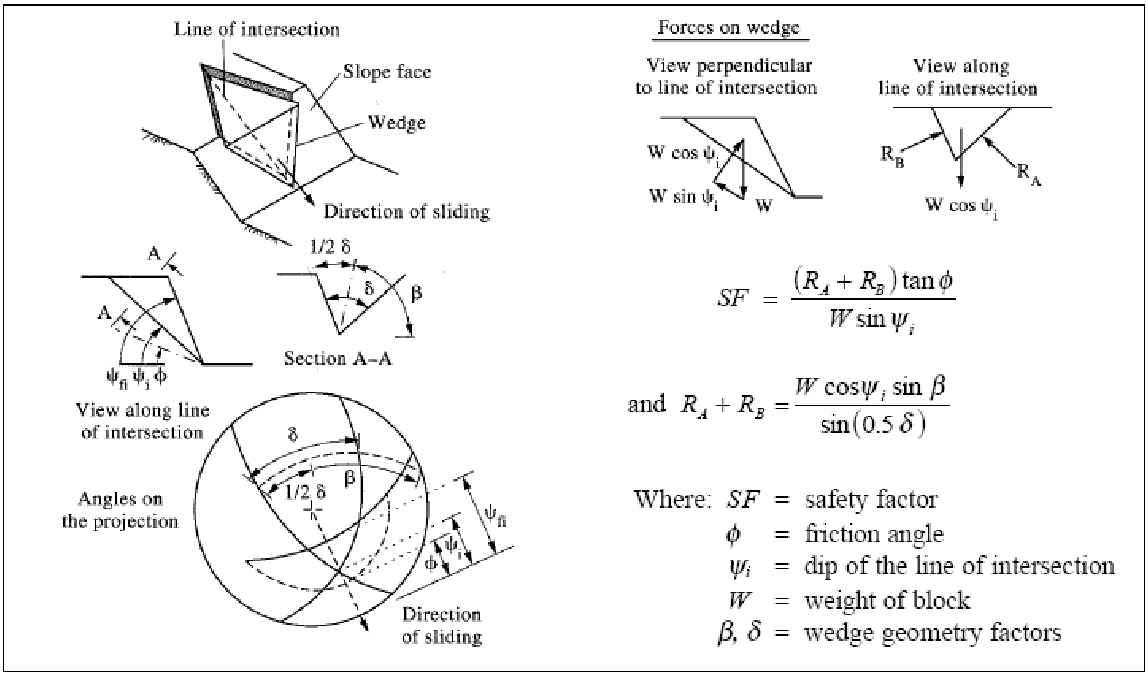

Fig 6. Calculation method of the analysis rock slope analysis in the form of wedge sliding

The one of the best software to plan analysis in slope is RocPlane. Therefore, RocPlane is an interactive software tool for performing planar rock slope stability analysis and design. RocPlane makes it easy to quickly create planar models, visualize them in both 2D and 3D, and evaluate analysis results. RocPlane contains many helpful features that allow users to rapidly build, modify and run models. RocPlane also includes functionalities for easily analyzing results, generating figures and charts, and producing convenient summaries of models and results. The report generation features of RocPlane are especially useful to engineers when writing reports with high quality and professional-looking drawings and diagrams. They help slope designers readily communicate findings to people with varying levels of slope engineering knowledge (Figures 5 and 8).

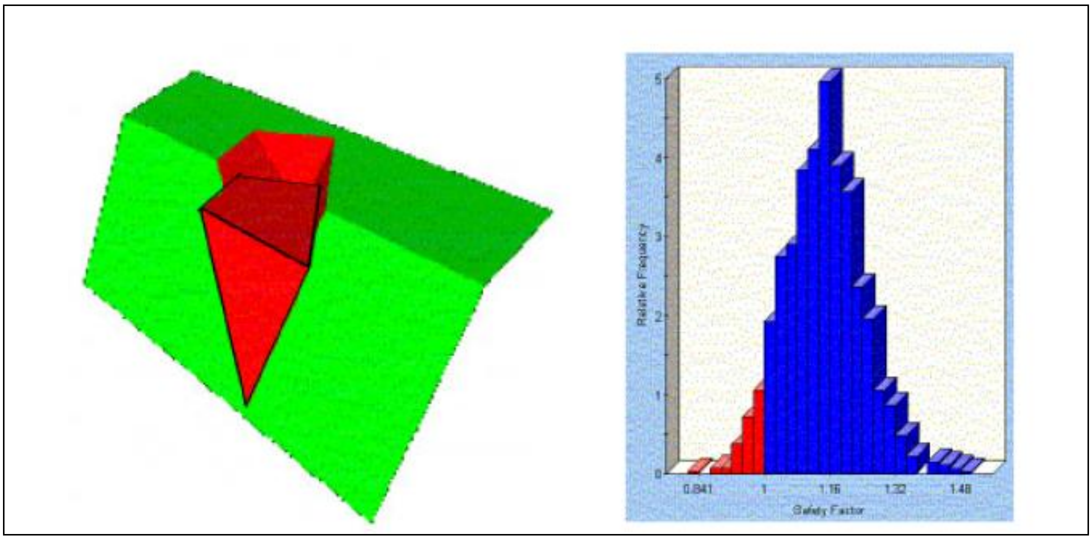

Fig 7. Probable limited equilibrium gap analysis (relative frequency refers to the number of valid gaps formed by Font Carlo sampling of input data)

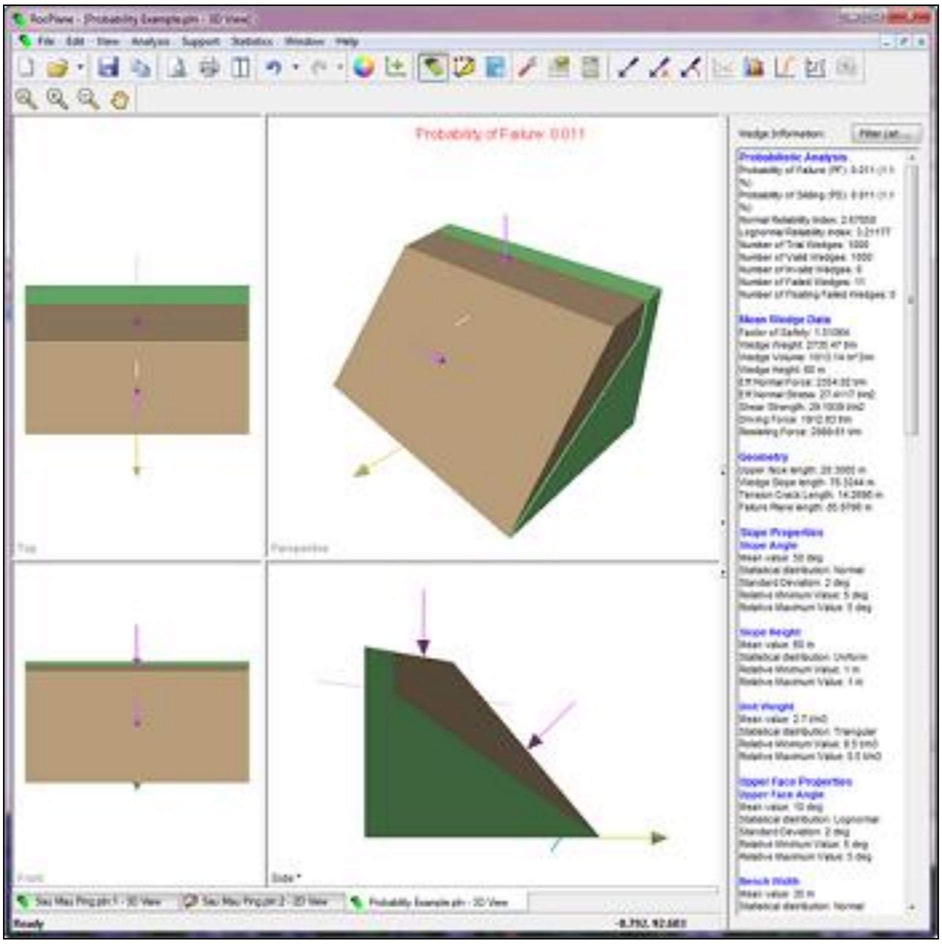

Fig 8. Calculation method of the analysis of rock slopes in the form of planar slide with RocPlane software

Another the best software to wedge analysis is SWedge, As, SWedge is a quick and simple-to-use analysis tool for evaluating the geometry and stability of surface wedges in rock slopes. It evaluates the geometry and stability of surface wedges in rock slope and defines tetrahedral (or pentahedral) surface wedge models formed by the intersection of two or three discontinuity planes to understand the most complex geometry and stability of surface wedges. This tool provides an integrated graphical environment for fast, easy data entry and 3D model visualization (Figures 7 and 9).

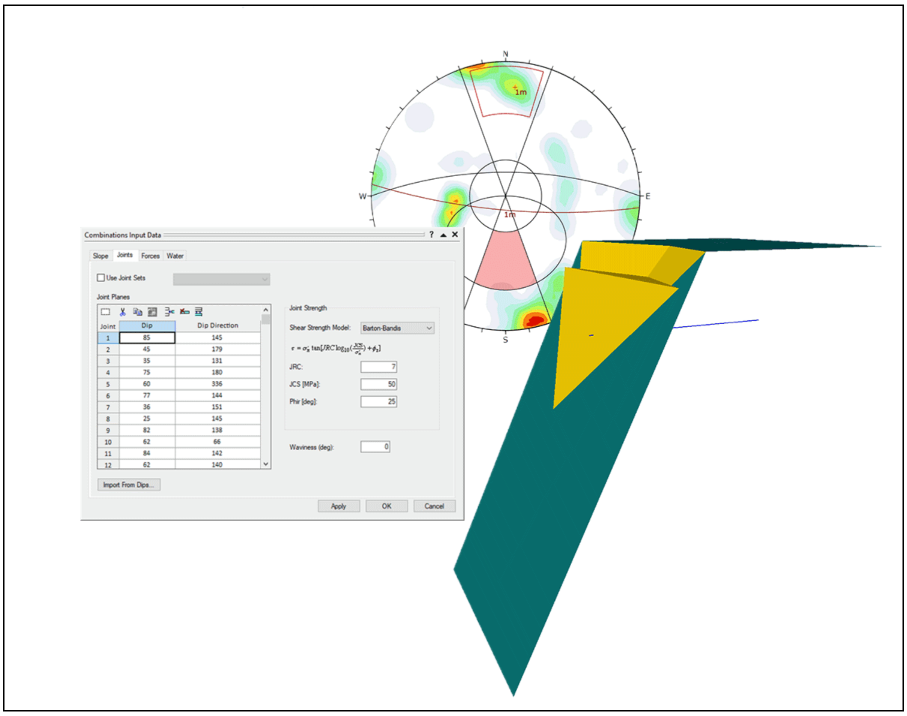

Fig 9. Calculation method of the analysis of rock slopes in the form of planar slide with SWadge software

2.2.4. Overturning analysis

Also, there are tools for direct overturning modes of rock fall, (similarly, there are solutions for overturning in screws, but since these spills have internal block deformations, very few finite equilibrium techniques are used for them). Direct overturning occurs when the center of gravity of the differentiated block is outside the outer line of the block bed; with the result that the critical moment of overturning will expand. Other considerations include the possibility of the block sliding or both overturning and sliding at the same time. (Figure 10)

As a result, the limited equilibrium analysis of overturning should consider both the possibility of overturning or sliding. (Figure 11). Action forces and limited equilibrium conditions for overturning and sliding of the two-dimensional block on the stepped foundation are shown. The solution process is similar to what was stated by Hoek and Berry (1991); Blocks have been developed to consider the equilibrium conditions of the whole system. These represent a group of sliding blocks in the region. Stable blocks on top and a bunch of overturned blocks in the middle. These equations are easily programmed and provide fast computer calculations and images of slip and overturn potential (Figure 12).

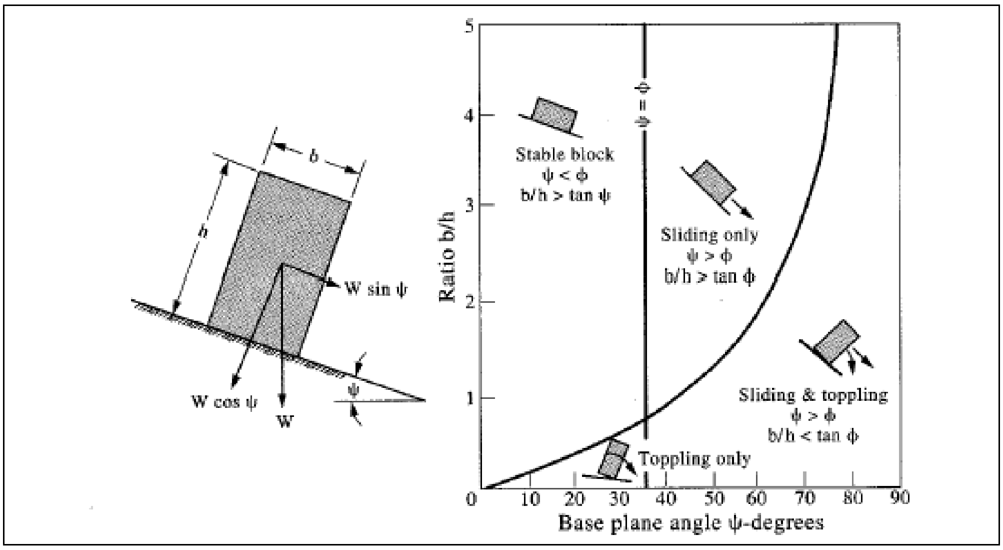

Fig 10. The ways slope and aspect affect the stability of the sliding type

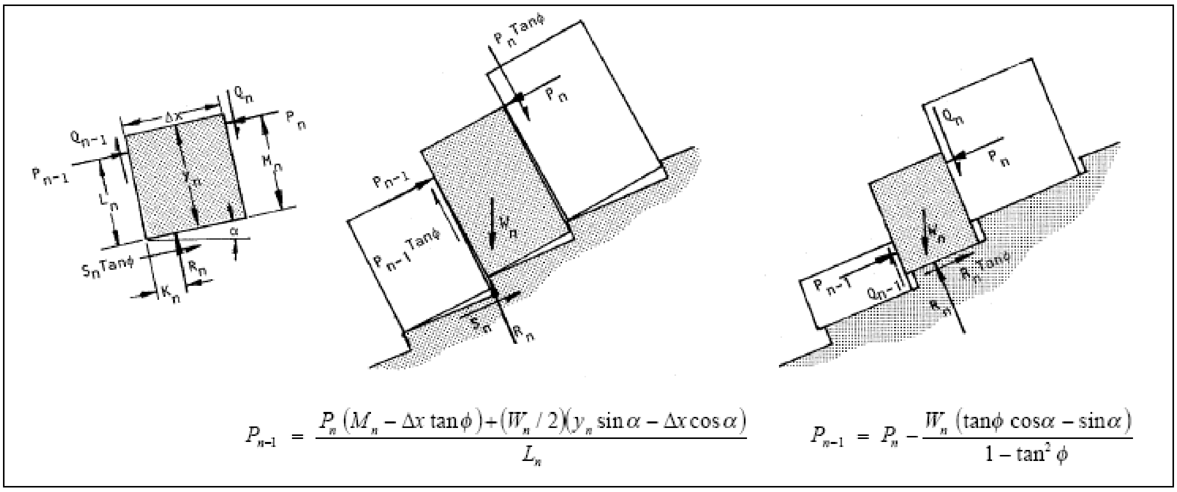

Fig 11. The effect of different forces on overturning slip

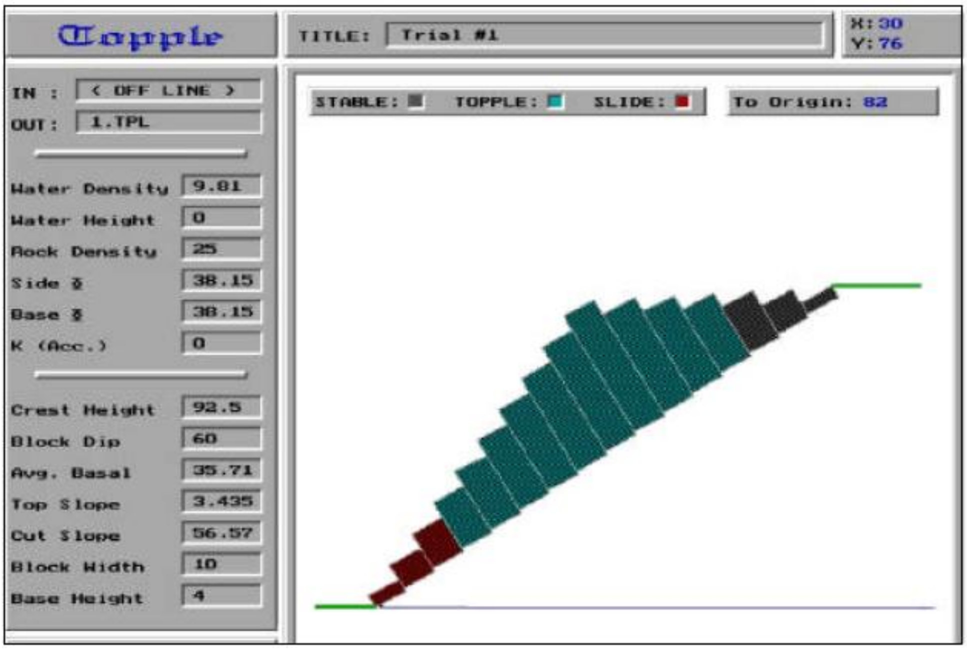

Fig 12. Analysis of boundary balance of sliding and overturning potential in rock slopes based on computer

2.2.5. Rotating analysis

In very weak rock, where the resistance of healthy materials is similar to the applied stresses, structural geology cannot control the states of stability and rupture; among the states that may occur in soils. Usually these states are circular ruptures; they are called rotations or slides with linear curvature.

In the analysis of rupture potential, one should pay attention to the position of the main sliding surface and determine its safety factor. Iterative solutions are used, each of which requires the selection of a sliding mass with the potential of instability, breaking the mass into parts (including the manner of the parts) and paying attention to the balance of force and torque applied to each part (Figure 13).

There are several methods, each of which is different according to the sub-structural assumptions adopted to determine the problem. In Table 1, these methods are briefly presented.

Detailed analysis based on these methods can be done quickly and effectively using computer calculations. Such analyzes lead to correct investigations in the field of the main sliding surface (Figure 14).

Such a method is very time-consuming if done manually. Boundary equilibrium programs, including the two-dimensional programs SLIDE (Rock Science 2001d) and SLOPE/W (GeoSlope 2000) and the three-dimensional program CLARA (Hanger 1992) have this ability with the heterogeneous behavior of the soil type and the geometries of the sliding surface and Model complex stereographs and variable pore water pressure conditions.

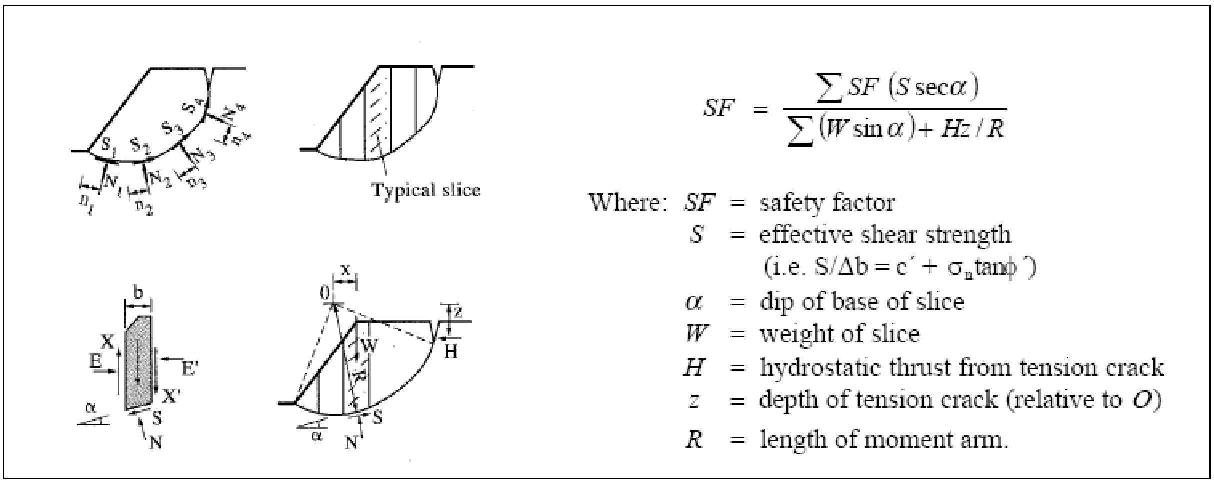

Fig 13. Boundary equilibrium solution related to circular rupture (adapted from Hudson and Harrison 1997)

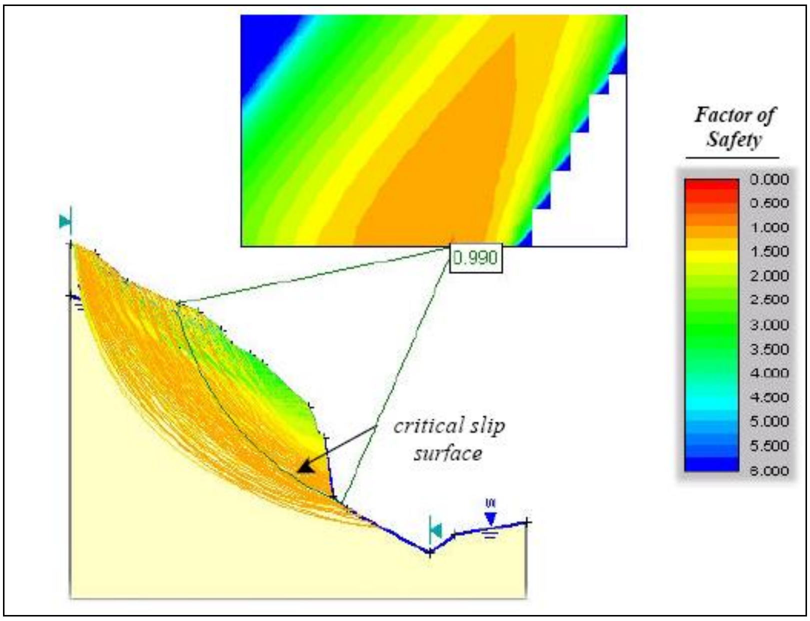

Fig 14. Boundary equilibrium analysis of a rock slope which is done using the main level research.

3. Discussion and investigation

3.1. Discontinuities in the spillway area

Among the many geological constructions, the discontinuities (layering, faults, seams and cracks, and vegetation) present in the rock mass are most effective in the stability of underground spaces and the support of dams. Discontinuities are structures that depend more on the tectonics and structural conditions of the region in terms of orientation, distance and number.

Various characteristics of rock mass discontinuities in the engineering geological unit of the studied area were collected using standard methods of ISRM (1981) in order to estimate rock engineering parameters using this information and properties of virgin rock. Discontinuities have been removed in a linear, windowed and scattered manner and as much as possible along the tunnel route. It should be noted that the selection of the location and type of harvesting stations was a function of the availability of stone outcrops.

The extractions done in the spillway route were equal to the number of 160 extractions. Figures 15 and 16 show the state of the seams and the rose diagram of the removed seams in the spillway route, and Table 2 presents the properties of the removed seams. Is. The joints were filled with clay and silt. These seams are related to folding and were created according to the prevailing tension conditions in the region. Table 2 shows the condition of the filling of the joints in the spillway area according to different materials.

Table 1. Specifications and opportunities taken from common methods used in boundary analysis of rotational slip ruptures (taken from Duncan 1996)

method	Constraints, opportunities and satisfactory equilibrium conditions
The usual way of parts	Low safety coefficients are inaccurate in surface slopes with high pore pressure. (Flenius 1927) is only suitable for circular slip design, it is assumed that the normal force applied to the base of each piece is W Cos (a); An equation (total mass torque balance) one
The modified method of Bishab(Bishab1995)	An accurate method is only for circular sliding surfaces; provides vertical balance and overall moment balance; With the assumption that the lateral forces are horizontal parts. Equations and unknowns:
Power balance methods	The force satisfies the applied force balance for any shape of the sliding surface, assuming that the slopes of the lateral force may be the same in all parts or that they may be different in each part, the partial slopes of the lateral force cause the amount of force to be less than that of the method. be the calculated applications that satisfy all equilibrium conditions,
John Boe's Simplified Method (1968)	The force balance method applied to any form of sliding surface assuming that the lateral forces are horizontal (same for all parts), the safety factors are usually significantly lower than the calculated applied methods that all equilibrium conditions satisfies
Modified method (US Army Corps of Engineers in 1970)	The force balance method that is used for any form of sliding surface with the assumption that the slopes of the lateral force are equivalent to the slope of the inclined surface; (They are the same for all parts) Safety factors are often significantly higher than calculated practical methods that meet all conditions.
The method of Lowe and Karafias in 1960	It is usually the most accurate method of force balance, which is used for any form of sliding surface, with the assumption that the slopes of the lateral surface are the average of the slope and the sliding surface (they are different in each piece), it provides horizontal and vertical force balance.
Spencer method 1967	It satisfies all conditions of equilibrium. It is applied to any shape of the sliding surface with the assumption that the slopes of the lateral forces are similar in each section; Slopes of lateral forces are calculated in the solution process in such a way that all balance conditions are met; It is a precise method.
Morgenstern method	Morgenstern satisfies all equilibrium conditions and is used for any form of sliding surface; With the assumption that Shibhay and Prisce in 1965 lateral forces are subject to a certain pattern; The slopes of the lateral forces can be similar or each part can be different; Lateral force gradients in the solution process are calculated in such a way that all equilibrium conditions are provided; It is a precise method;

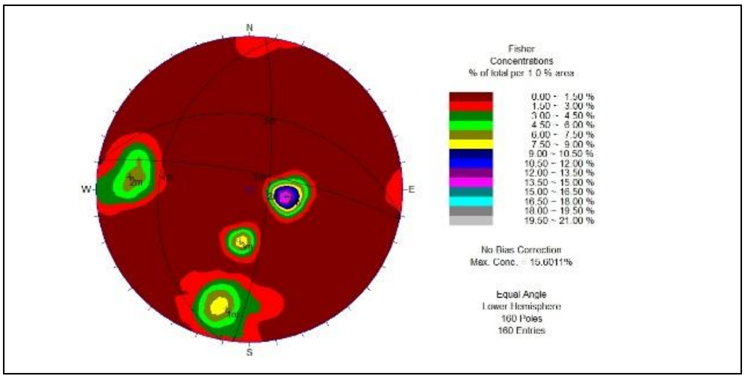

Fig 15. A view of the condition of the seams in the spillway area

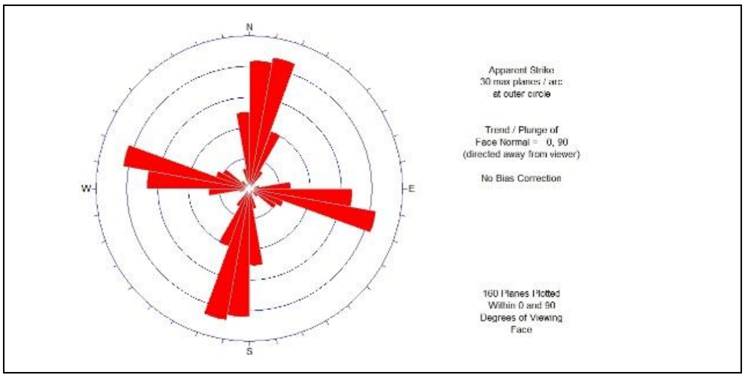

Fig 16. A view of the state of the rose diagram in the spillway area

Table 2. Specifications of the seams removed in the spillway area (author)

roughness		Opening (mm)		length (meters)				distance (cm)				Geometric features		discontinuity
wavy - rough	smooth-rough	0.5-10	>0.5	>10	3–10	1–3	>1	>200	60–200	20–60	6–20	steep direction	slope	
22	78	30	70	8	44	48	0	020	33	9	12	011	77	J1
0	100	0	100	0	44	56	0	47	27	20	6	096	76	J2
0	100	18	82	0	17	75	8	18	55	27	0	010	38	J3
0	100	0	100	100	0	0	0	20	34	31	15	281	29	BEDDING

2.3. Determining the classifications of rocks in the spillway area

In order to determine the geomechanical parameters of the rock mass, the engineering classification of the rock mass was done using the results of laboratory tests and field surveys to estimate and present the geomechanical parameters of the rock mass in the studied area. The method used for the engineering classification of rock masses is to calculate GSI, Q and RMR based on the information obtained from the drilled boreholes in the study area. Based on the aforementioned, GSI index and RMR and Q values were calculated and the results are presented in Table 3.

Table 3. The results of classification of rock masses in the studied area

Condition	GSI	RMR	Q
dry	35-42	63-71	3.26-8.34
Saturation	35-42	54-63	2.97-5.51

According to the measurements taken from the dam construction, the classification values of Q and RMR have been taken, and the relationship between them is presented in Figures 17 to 20.

The purpose of this adaptation is not to present a new relationship between the systems, but rather to control and ensure the correctness of different classifications. Due to the fact that the systems are not completely equivalent and each of the classification systems shows more emphasis on special parameters. Therefore, obtaining a high convergence in the matter of compatibility is not a criterion for the correctness of the work, but the closeness of the obtained result to the existing results proposed by other researchers is the criterion of the correctness of the work. For example, obtaining a convergence coefficient of 1 for two RMR-Q classification systems will not prove the correctness of the work.

These two systems, which were proposed one year apart from each other, are among the most widely used classification systems and have the most compatibility among the systems. There are countless statistical equations of relationships that have been proposed by different researchers during the lifetime of these two systems, and in this research, the best relationship between these parameters has been presented based on linear, exponential, and logarithmic relationships, and the best fit between the data is logarithmic which is presented in Figure 20.

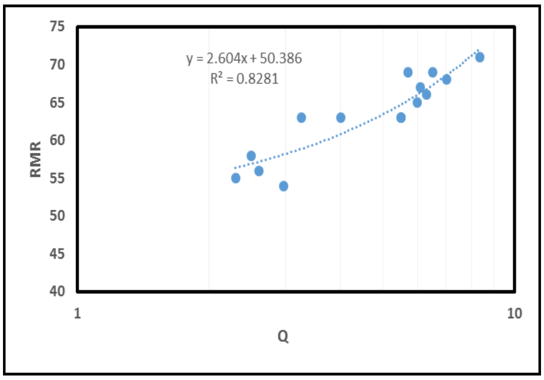

Fig 17. Linear relationship between Q and RMR classification system

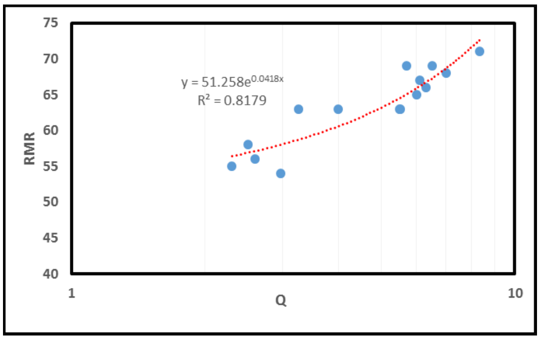

Fig 18. Exponential relationship between Q and RMR classification system

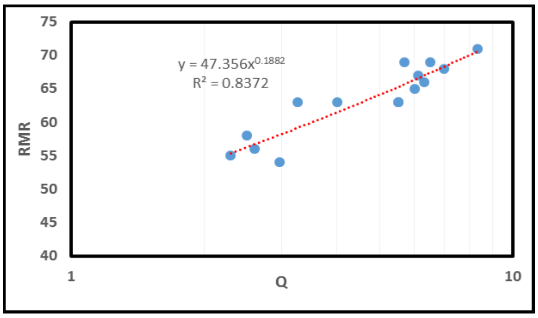

Fig 19. Power relationship between Q and RMR classification system

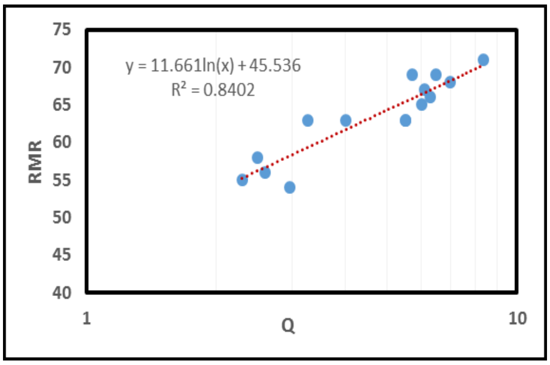

Fig 20. Logarithmic relationship between Q and RMR classification system

3.3. Analysis of the stability of the spillway trench head

Various methods are used to check and evaluate the head of the spillway trench. According to the drawn cross-section, it shows that the amount of excavation in the spillway will be about 20 meters. In the following, it is stated that different methods are used to check the stability of spillway walls.

➢ **Use of discontinuities**

According to the condition of the seams mentioned in Table 1, it can be stated that this area had 3 seams and one layering, which is shown in Figure 21. In order to check the mode of rupture, the Schmitt network was used, which considering that the slope considered for the spillway is 72 degrees, therefore, in Figure 21, the condition of the joints has been shown in relation to the slope and the direction of the slope of the exit of the spillway opening, and the probability of sliding is There is a planar face for the J3 joint, and considering the condition of the joints, we can also expect a wedge break.

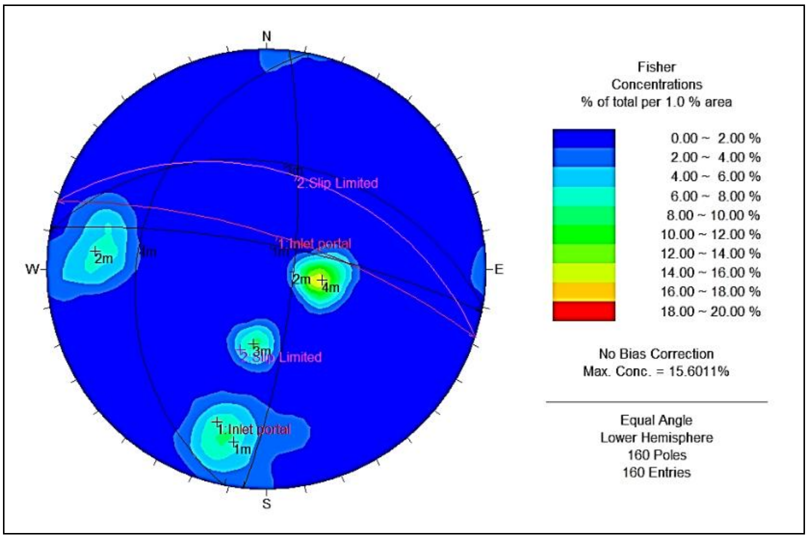

Fig 21. The condition of the joints and the slope of the spillway outlet range

➢ **Planar rupture analysis**

In this analysis, Rocplane software from the RocScience software series is used, which in this analysis is modeled as dry, saturated, and earthquake acceleration. Figure 22 shows the condition of planar rupture in the dry state in the spillway, and in this case, the safety factor of the wall is equal to 2.13. Figure 23 shows the state and specifications of the sliding screen. If the spillway area becomes saturated, it will cause planar sliding in this spillway, which is shown in Figure 24 of the condition and characteristics of planar sliding in a fully saturated state, and in a saturated state, the safety factor will be equal to 1.74. Figure 25 shows the sensitivity analysis of the saturation percentage (fullness) with the safety factor of plate breakage, in this case, the more the saturation percentage is added, the safety factor of breakage will decrease.

If it is applied to the earthquake structure, it will reduce the safety factor, which is shown in Figure 26, the state and characteristics of planar rupture in the spillway due to the existence of an earthquake. In this case, the safety factor of plate breakage will be equal to 1.14. Figure 2273 shows the sensitivity analysis of the safety factor of planar rupture in the spillway with respect to the changes in earthquake acceleration, which has caused a decrease in the safety factor in sliding with the increase in earthquake acceleration in the region.

If there is water and earthquake acceleration in the area, it will reduce the safety factor, as shown in Figure 28, in this case, the safety factor of rupture will be equal to 1.12.

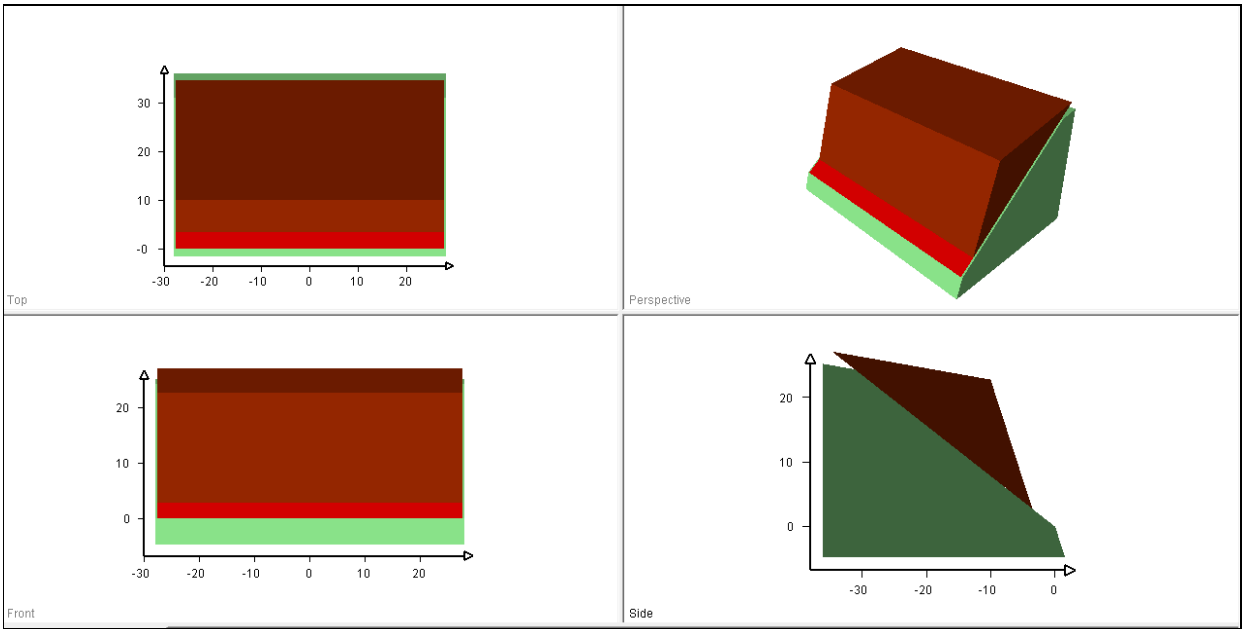

Fig 22. The condition of planar rupture in the spillway

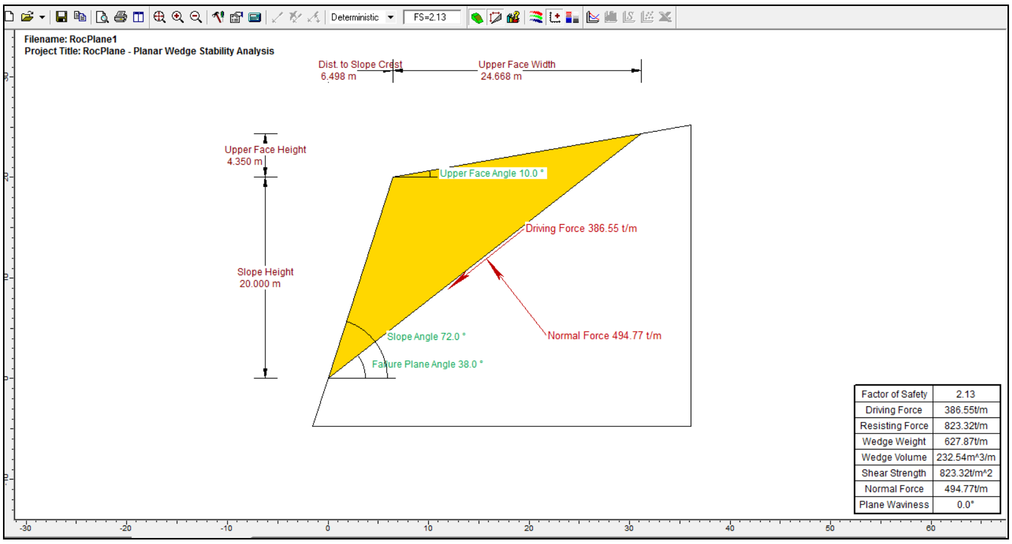

Fig 23. Planar sliding characteristics in the dry state in the spillway

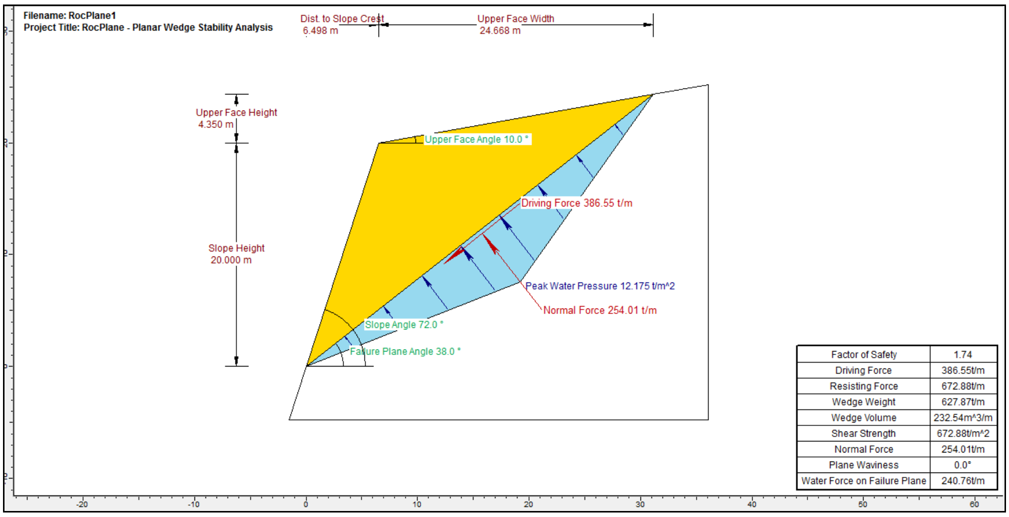

Fig 24. Plate sliding characteristics in the saturated state in the spillway

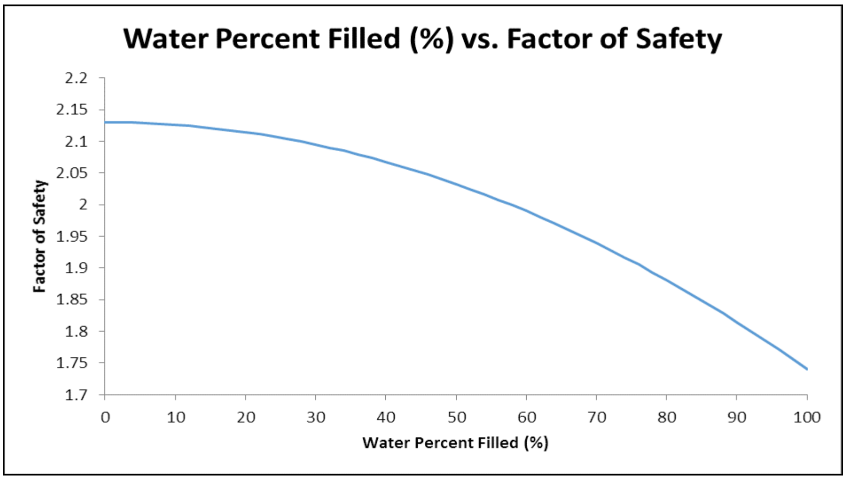

Fig 25. Sensitivity analysis of planar rupture safety factor with percentage of filling (saturation)

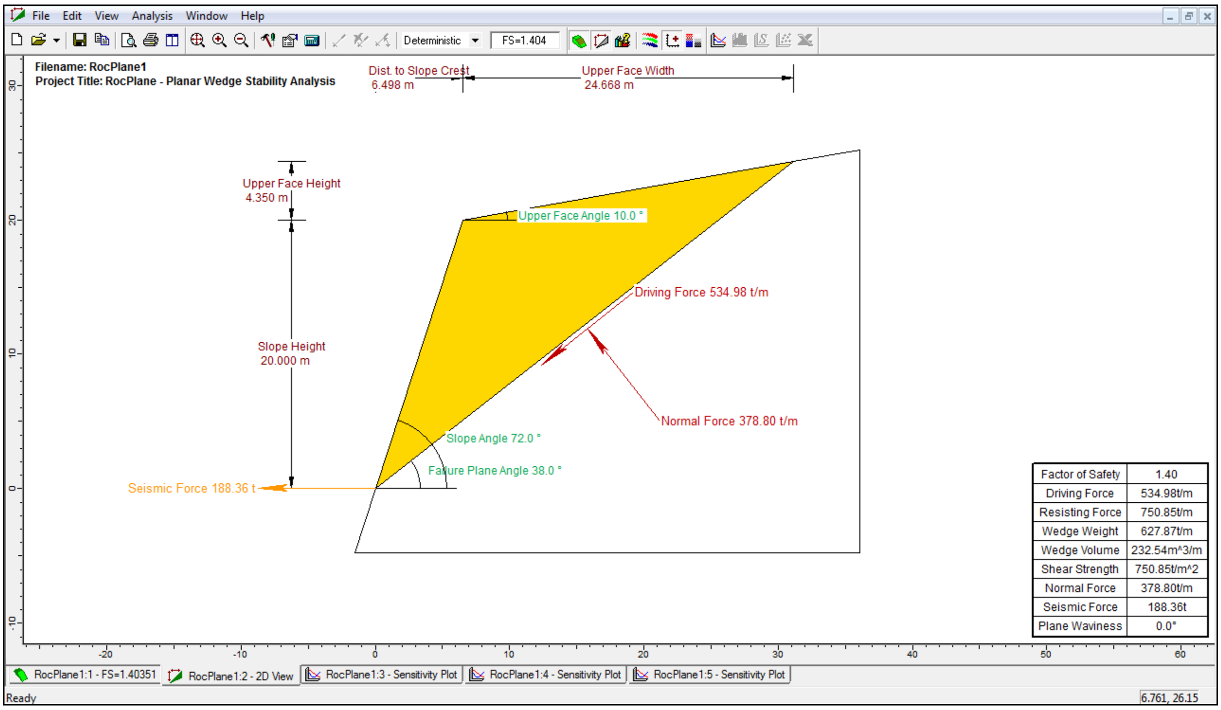

Fig 26. Characteristics of planar rupture created during the earthquake

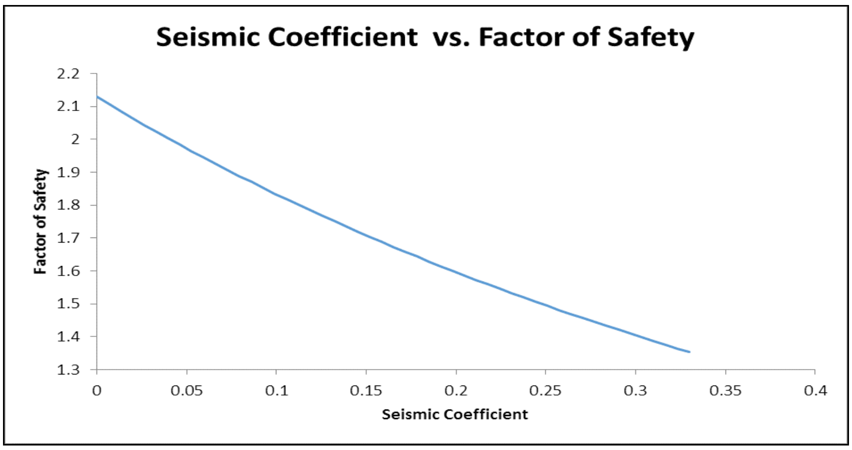

Fig 27. Sensitivity analysis of planar rupture safety factor with changes in earthquake acceleration

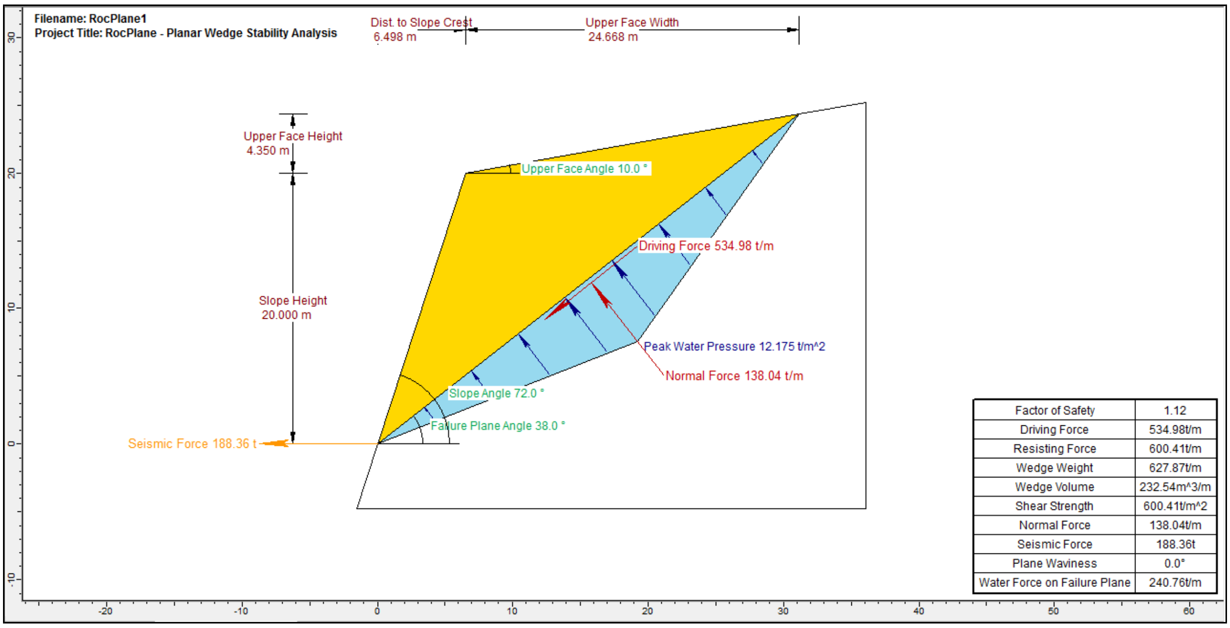

Fig 28. Planar rupture characteristics in case of earthquake and saturation

- **Wedge rupture**

Swedge software from Rocscience software series has been used to check wedge breakage. Which in this analysis is modeled as dry and saturated and earthquake acceleration.

Figure 29 shows the state of wedge rupture in the dry state in the spillway, in which the safety factor of the wall is equal to 3.7. If the spillway area becomes saturated, it will cause the wedge to break in this spillway, which is shown in Figure 30 of the state and characteristics of the wedge slip in the fully saturated state, and in the saturated state, the safety factor will be equal to 0.0. In this case, the more the percentage of saturation is added, the less the breakage safety factor will be.

If it is applied to the earthquake structure, it will reduce the safety factor, which is shown in Figure 31, the condition and characteristics of wedge rupture in the spillway due to the existence of an earthquake. In this case, the safety factor of plate breakage will be equal to 2.69 which has decreased the safety factor in landslides with the increase in the earthquake acceleration in the region.

If there is water and acceleration of the earthquake in the area, it will reduce the safety factor, which is shown in Figure 32. In this case, the safety factor of rupture will be equal to 0.0.

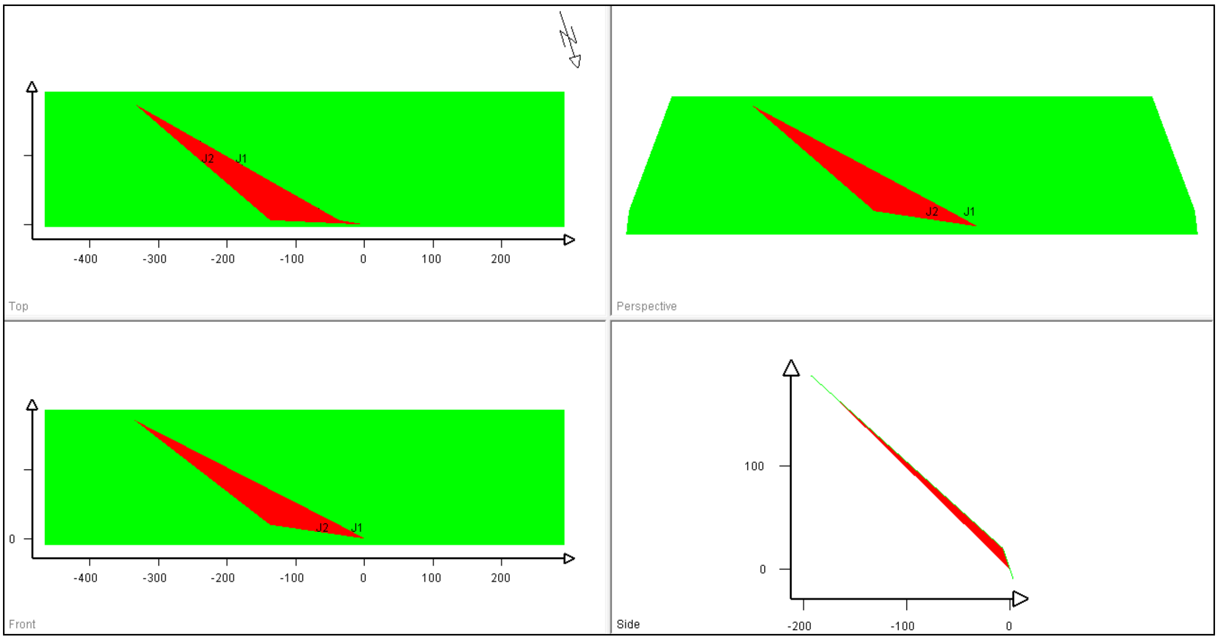

Fig 29. Wedge rupture condition in spillway in dry state

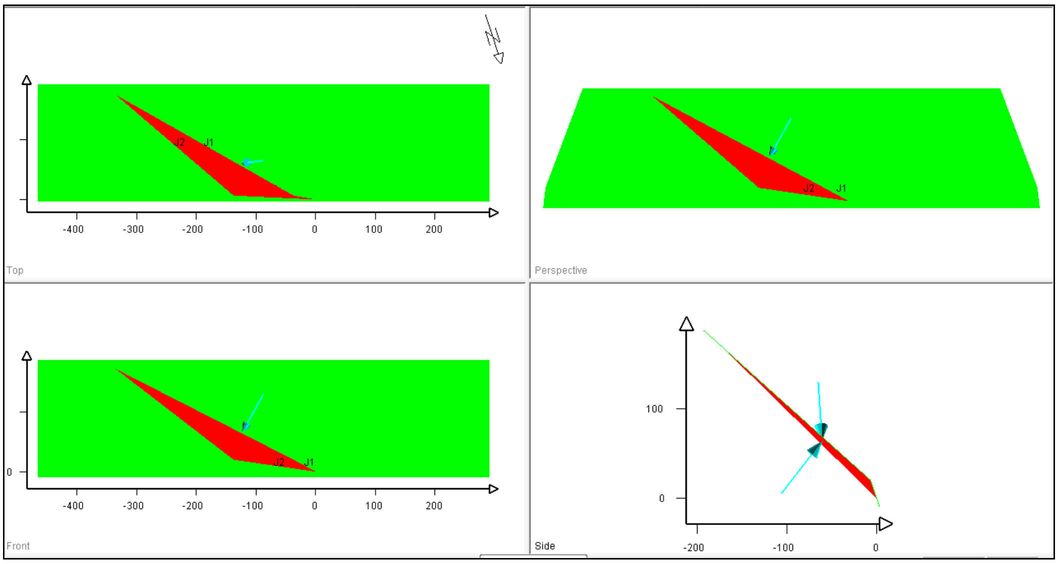

Fig 30. Wedge rupture condition in spillway in saturated state

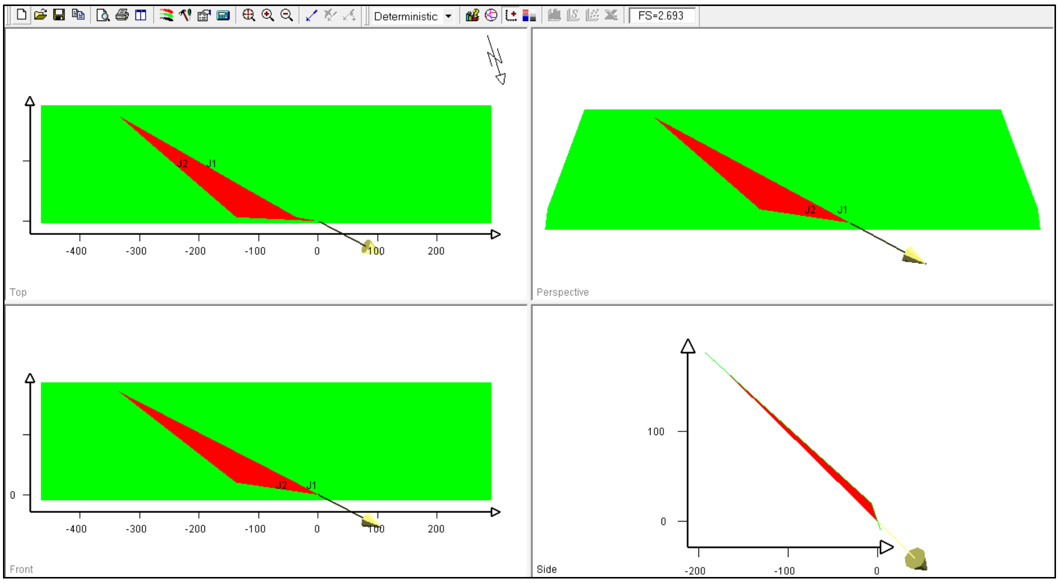

Fig 31. Wedge rupture condition in spillway in earthquake mode

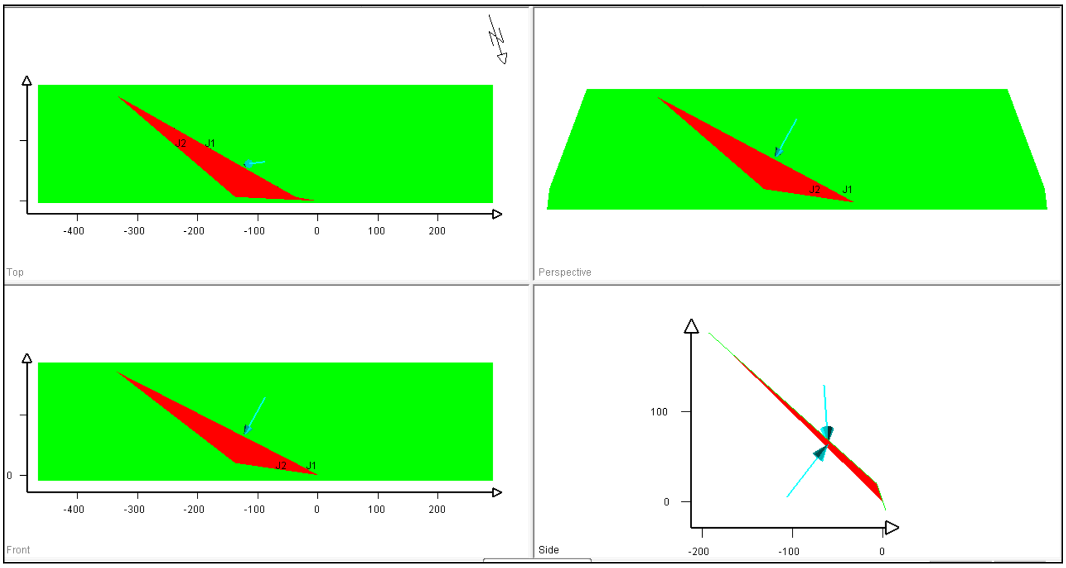

Fig 32. The state of wedge rupture in the spillway in the state of saturation and earthquake

4. Conclusion

These papers present a systematic study of kinematical and limit equilibrium-based methods (LEMs) that are utilized for discontinuous rock stability analyses as well as for limit-equilibrium methods for jointed rock which are implemented in two-dimensional and three-dimensional spaces. During as decades, various approaches were developed by scholars to estimate the slope stabilities. To this end, the main methodologies of LEMs have been examined and their approaches through history have been described. The LEMs have been improved and modified to cover applications ranging from simplified circular failure analysis to high-order solutions of complex failures. Finally, the most advanced method of rock slope stability assessment that has been widely used by researchers nowadays and named as 'Block theory' that is based on strong computational and analytical foundations has been considered. In this regard, a brief overview of the new decade's achievements on Goodman's theory, which reflects modification of Block theory over time has been mentioned and discussed. As outlook of the LEMs, these approaches due to the flexibility can be coupled with the new procedure like numerical and hybrid methods and provide the simple and fast implementation for slope stability assessments. On the other hand, the application of new theories such as Block theory provides simple mathematical decryption for both structural and stress-field failures which is highly efficient in combination with numerical procedures like distinct of finite elements. In terms of the future scope for LEMs-based slope stability especially Block theory, it can be notified that Goodman's theorem can be considered as the strongest approach to quantify the discontinuous rock slope and estimate the slope's stability condition

For reconstruction project of spillway of Gabric Dam, the stability of the slope on both banks is crucial to the safety of the project. Because of the complex geological conditions after the earthquake, and lack of detailed survey information, it was very difficult to determine the strength parameters of rock mass. Based on the stability analysis of slope, a strength parameters inversion method was presented. Based on the results, the stability of the slope was analyzed and the effect of reinforcement was evaluated, The most important outcomes are the followings:

- The studied area is located in the Makran area in the sedimentary structural division of Iran.
- The stratigraphic units in the spillway area include the SM unit, which includes sandstone and sandstone with interlayers of marl and silty marl.
- The quality index of the rock mass in the spillway area is in the medium to good category.
- According to the climatic conditions of the region and the erodibility of the units, it is recommended to use mesh and shotcrete covering along with the design of surface and deep drainage during excavation in the drainage area.
- Also, during the excavation of the spillway, according to the condition of the joints, the necessary precautions should be taken to prevent plate and wedge slips in the trenches.
- According to the analyzes done, a planar rupture can be seen in the head of the trench, which according to the obtained results shows that if the spillway area is saturated, it will cause a plate slip in this spillway will be 1. And according to the sensitivity analysis of the percentage of saturation (filling) with the safety coefficient of plate breakage, it shows that in this case, the more the percentage of saturation is added, it will decrease the safety coefficient of breakage.
- If it is applied to an earthquake structure, it will reduce the safety factor, and in this case, the safety factor of planar rupture will be equal to 1.14 and the sensitivity analysis of the safety factor of planar rupture in the spillway with respect to the changes in earthquake acceleration shows that the increase in earthquake acceleration in the region has caused a decrease in the safety factor in sliding. If there is water and acceleration of the earthquake in the area, it will reduce the safety factor, which in this case, the safety factor of rupture will be equal to 1.12.

References

Abramson LW, Lee TS, Sharma S, Boyce GM (2001) Slope stability and stabilization methods. John Wiley \& Sons

Akgun A (2012) A comparison of landslide susceptibility maps produced by logistic regression, multi-criteria decision, and likelihood ratio methods: A case study at İzmir, Turkey. Landslides 9:93–106. https://doi.org/10.1007/s10346-011-0283-7

Akgün H, Koçkar MK (2004) Design of anchorage and assessment of the stability of openings in silty, sandy limestone: a case study in Turkey. Int J Rock Mech Min Sci 41:37–49

Alashti MS (2018) New Empirical Relations for Determination of Rock Slope Safety Factor in Fully Drained Conditions on Section RS06 of Block five in Sungun Copper Mine. East African Sch Multidiscip Bull 4413:61–121

Ansari T, Kainthola A, Singh KH, et al (2021) Geotechnical and micro-structural characteristics of phyllite derived soil; implications for slope stability, Lesser Himalaya, Uttarakhand, India. Catena 196:104906

Arjmandzadeh R, Sharifi Teshnizi E, Rastegarnia A, et al (2019) GIS‐Based Landslide Susceptibility Mapping in Qazvin Province of Iran. Iran J Sci Technol Trans Civ Eng. https://doi.org/10.1007/s40996-019-00326-3

Asfaw L, Meten M, Garo T (2022) Leakage and abutment slope stability analysis of Arjo Didesa dam site, western Ethiopia. Arab J Geosci 15:1540

Asthana BN, Khare D (2022) Foundation Treatment of Dams. In: Recent Advances in Dam Engineering. Springer, pp 185–219

Attia M, Abdel Razek M, Salam AA (2021) Seepage through earth dams with internal cut off. Geotech Geol Eng 39:5767–5774

Azarafza M, Akgün H, Asghari-Kaljahi E (2017) Assessment of rock slope stability by slope mass rating (SMR): A case study for the gas flare site in assalouyeh, South of Iran. Geomech Eng 13:571–584. https://doi.org/10.12989/gae.2017.13.4.571

Azarafza M, Akgün H, Ghazifard A, et al (2021) Discontinuous rock slope stability analysis by limit equilibrium approaches–a review. Int J Digit Earth 14:1918–1941. https://doi.org/10.1080/17538947.2021.1988163

Azarafza M, Ghazifard A (2016) Urban geology of Tabriz City : Environmental and geological constraints. Adv Environ Res 5:95–108. https://doi.org/10.12989/aer.2016.5.2.095

Barton N (1978) Recent experiences with the Q-system of tunnel support design

Barton N, Lien R, Lunde J (1974) Engineering classification of rock masses for the design of tunnel support. Rock Mech 6:189–236. https://doi.org/https://doi.org/10.1007/BF01239496

Barton N, Løset F, Lien R, Lunde J (1981) Application of Q-system in design decisions concerning dimensions and appropriate support for underground installations. In: Subsurface space. Elsevier, pp 553–561

Bertolini G (2010) Large earth flows in Emilia-Romagna (Northern Apennines, Italy): origin, reactivation and possible hazard assessment strategies. Zeitschrift der Dtsch Gesellschaft für Geowissenschaften 161:139–162

Bieniawski ZT (1993) Classification of rock masses for engineering: the RMR system and future trends. In: Rock Testing and Site Characterization. Elsevier, pp 553–573

Bieniawski ZT, Pells PJ, Hencher SR, Pells SE (2017) Rock quality designation (RQD): time to rest in peace. Can Geotech J 54:825–834

Bolton Seed H, Duncan JM (1987) The failure of Teton Dam. Eng Geol 24:173–205. https://doi.org/10.1016/0013-7952(87)90060-3

Briggs S, Huebner M, AbramsonWard H, et al (2019) Geologic Influences on Slope Stability and Foundation Design, Oroville Dam Spillway, California. In: IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018-Volume 4: Dams, Tunnels, Groundwater Resources, Climate Change. pp 33–40

Dahoua L, Usychenko O, Savenko VY, Hadji R (2018) Mathematical approach for estimating the stability of geotextile-reinforced embankments during an earthquake. Min Sci 25:207–217

Davoudi S, Siosemarde M, Merufinia E (2014) Evaluation of Stability of Spillway Gable Roof of Nazlu Dam via Slide Software. J homepage http//www ojceu ir/main 3:274–281

Duncan JM (1996) State of the art: limit equilibrium and finite-element analysis of slopes. J Geotech Eng 122:577–596

Fredj M, Hafsaoui A, Riheb H, et al (2020) Back-analysis study on slope instability in an open pit mine (Algeria). Natsional'nyi Hirnychyi Universytet Nauk Visnyk 24–29

Ghorbani M (2021) The geology of Iran: tectonic, magmatism and metamorphism. Springer

Ghorbani M, Ghorbani M (2013) A summary of geology of Iran. Econ Geol Iran Miner Depos Nat Resour 45–64

Grayaa AC, Louati S (2022) Numerical Modeling of a Pathological Case: Spillway of Joumine Dam Tunisia. In: 2nd International Conference on Advances in Rock Mechanics-TuniRock 2022

Gupta V, Bhasin RK, Kaynia AM, et al (2016) Finite element analysis of failed slope by shear strength reduction technique: a case study for Surabhi Resort Landslide, Mussoorie township, Garhwal Himalaya. Geomatics, Nat Hazards Risk 7:1677–1690

Hammah RE, Curran JH, Yacoub T, et al (2004) Stability analysis of rock slopes using the finite element method. In: Proceedings of the ISRM regional symposium EUROCK

Hammah RE, Yacoub T, Corkum B, et al (2007) Analysis of blocky rock slopes with finite element shear strength reduction analysis. In: 1st Canada-US Rock Mechanics Symposium

Hoek E (2002) A brief history of the development of the Hoek-Brown failure criterion

Hoek E, Brown ET (2019) The Hoek–Brown failure criterion and GSI – 2018 edition. J Rock Mech Geotech Eng 11:445–463. https://doi.org/10.1016/j.jrmge.2018.08.001

Hoek E, Carranza-Torres C, Corkum B (2002) Hoek-Brown failure criterion-2002 edition. Proc NARMS-Tac 1:267–273

Ietto F, Perri F, Cella F (2018) Weathering characterization for landslides modeling in granitoid rock masses of the Capo Vaticano promontory (Calabria, Italy). Landslides 15:43–62. https://doi.org/10.1007/s10346-017-0860-5

Johari A, Lari AM (2016) System reliability analysis of rock wedge stability considering correlated failure modes using sequential compounding method. Int J Rock Mech Min Sci 82:61–70

Johari A, Momeni M, Javadi AA (2015) An analytical solution for reliability assessment of pseudo-static stability of rock slopes using jointly distributed random variables method

Karimizad N, Teshnizi ES, Mahdad M, Karimiazar J (2020) Investigating the design features of CSG dams. JOJ Sci 2:60–66. https://doi.org/10.19080/JOJS.2020.02.555588

Kumar PR, Muthukkumaran K (2022) Numerical Analysis on Stability Assessment of Left Bank Rock Slopes, Polavaram Irrigation Tunnel. In: Dynamics of Soil and Modelling of Geotechnical Problems: Proceedings of Indian Geotechnical Conference 2020 Volume 5. pp 255–265

Li W, Wu W, Zhang J (2022) Numerical stability analysis of the dam foundation under complex geological conditions at great depth: a case study of Kala Hydropower Station, China. Front Phys 9:851

Liu S, Su Z, Li M, Shao L (2020) Slope stability analysis using elastic finite element stress fields. Eng Geol 273:105673. https://doi.org/10.1016/j.enggeo.2020.105673

Liu T, Deng J, Zheng J, et al (2017) A new semi-deterministic block theory method with digital photogrammetry for stability analysis of a high rock slope in China. Eng Geol 216:76–89

Marinos PG, Hoek E (2000) GSI: a geologically friendly tool for rock mass strength estimation. In: ISRM international symposium. 19-24 November, Melbourne, Australia, p 19

Nassirzadeh Goorchi R, Amini M, Memarian H (2019) Assessment of Slope Stabilization Based on Probabilistic Analysis Results (Case Study: Slope Facing Spillway of Kavar Dam in Shiraz). J Eng Geol 13:371–398

Ozbek SE (2017) Numerical Modeling of Seepage in Koyunbaba Dam. University of Akron

Palmström A (2009) Combining the RMR, Q, and RMi classification systems. Tunn Undergr Sp Technol 24:491

Palmström A (1996) Characterizing rock masses by the RMi for use in practical rock engineering: Part 1: The development of the Rock Mass index (RMi). Tunn Undergr Sp Technol 11:175–188

Poorbehzadi K, Yazdi A, Sharifi Teshnizi E, Dabiri R (2019) Investigating of Geotechnical Parameters of Alluvial Foundation in Zaram-Rud Dam Site, North Iran. Int J Min Eng Technol 1:33–44

Raghuvanshi TK (2019) Plane failure in rock slopes – A review on stability analysis techniques. J King Saud Univ - Sci 31:101–109. https://doi.org/10.1016/j.jksus.2017.06.004

Rastegarnia A, Sharifi Teshnizi E, Hosseini S, et al (2018) Estimation of punch strength index and static properties of sedimentary rocks using neural networks in south west of Iran Estimation of punch strength index and static properties of sedimentary rocks using neural networks in south west of. Iran Meas. https://doi.org/10.1016/j.measurement.2018.05.080

Ribas JR, Severo JCR, Guimaraes LF, Perpetuo KPC (2021) A fuzzy FMEA assessment of hydroelectric earth dam failure modes: A case study in Central Brazil. Energy Reports 7:4412–4424

Romana M, Tomás R, Serón JB, others (2015) Slope mass rating (SMR) geomechanics classification: thirty years review. In: 13th ISRM International Congress of Rock Mechanics

Romana MR (1993) A geomechanical classification for slopes: slope mass rating. In: Rock testing and site characterization. Elsevier, pp 575–600

Romana Ruiz M, Serón Gáñez JB, Montalar Yago E (2001) La clasificación geomecánica SMR: Aplicación, Experiencias y Validación. In: V Simposio Nacional sobre Taludes y Laderas Inestables: Madrid, Spain

Sadeghi S, Sharifi Teshnizi E, Ghoreishi B (2020) Correlations between various rock mass classification / characterization systems for the Zagros tunnel-W Iran. J Mt Sci 17:1790–1806. https://doi.org/10.1007/s11629-019-5665-7

Sadeghpour A, Asgari J, Mojezi M (2008) Study of Instability Event of Rock Trench In Vanyar Dam Spillway. In: Sixth International Conference on Case Histories in Geotechnical Engineering, Missouri University of Science and Technology Scholars' Mine

San Mauro J, Toledo MÁ, Salazar F, Caballero FJ (2019) A methodology for the design of dam spillways with wedge shaped blocks based on numerical modeling. Rev Int métodos numéricos para cálculo y diseño en Ing 35:

Shangyi Z, Yingren Z, Weidong D, others (2003) Stability analysis on jointed rock slope by strength reduction FEM. Chinese J Rock Mech Eng 22:254–260

Sharifi Teshnizi E, Arjmandzadeh R, Rastegarnia A, Bakhshi A (2019) Geogrid design in soil improvement. Azarin Mehr Publisher, Iran, Tehran

Sharifi Teshnizi E, Golian M, Sadeghi S, Rastegarnia A (2022) Application of analytical hierarchy process (AHP) in landslide susceptibility mapping for Qazvin province, N Iran. Elsevier Inc.

Sharifi Teshnizi E, Hoseini Z, Babakhani P, Mohamadi Anaie H (2021a) Geodetic and Geotechnical Monitoring in Shallow and Urban Tunnels. Azarin Mehr, Tehran, Iran

Sharifi Teshnizi E, Hosseini S, Atoofian A, Babakhani P (2021b) The Excavation Methods of Ahallow Tunnel in Urban Area. Azarin Mehr, Tehran

Sharifi Teshnizi E, Reisi Dehkordi MS, Moaiedi Kia A, Jamgohari Y (2021c) The strategic management of ballast (design, maintenance). Supreme National Defense University, Tehran, Iran, Tehran

Sheen YN, Huang LJ, Le DH (2014) Engineering properties of controlled low-strength material made with residual soil and class F fly ash. Appl Mech Mater 597:345–348. https://doi.org/10.4028/www.scientific.net/AMM.597.345

Singh B, Goel RK (1999) Rock mass classification: a practical approach in civil engineering. Elsevier

Singh TN, Gulati A, Dontha L, Bhardwaj V (2008) Evaluating cut slope failure by numerical analysis—a case study. Nat hazards 47:263–279

Singh TN, Monjezi M (2000) Slope stability study in jointed rockmass—a numerical approach. Min Engg Jl 1:12–13

Singh TN, Singh DP (1992) Slope stability study in an opencast mine over previously worked seam. In: International Symposium on Rock Slope, New Delhi. pp 467–477

Singh TN, Ulabhaje A V, Singh DP, Gupta KK (1989) Planning of slope stability in opencast mine-A model study. In: 3 rd National Seminar on Surface Mining. Indian Mining \& Engineering Jour., Dhanbad. pp 1–5

Skempton AW (1984) Slope stability of cuttings in brown London clay. In: Selected Papers on Soil Mechanics. Thomas Telford Publishing, pp 241–250

Wu H-W, Li E, Sun Y, Dong B (2021) Research on the operation safety evaluation of urban rail stations based on the improved TOPSIS method and entropy weight method. J Rail Transp Plan \& Manag 20:100262. https://doi.org/10.1016/j.jrtpm.2021.100262

Wyllie DC, Mah C (2004) Rock slope engineering. CRC Press

Yang XL, Liu ZA (2018) Reliability analysis of three-dimensional rock slope. Geomech \& Eng 15:1183–1191

Yang Y, Sun G, Zheng H (2019) Stability analysis of soil-rock-mixture slopes using the numerical manifold method. Eng Anal Bound Elem 109:153–160. https://doi.org/10.1016/j.enganabound.2019.09.020

Yingren Z, Shangyi Z (2004) Application of strength reduction FEM in soil and rock slope. Chinese J Rock Mech Eng 23:3381–3388

Youssef AM, Pourghasemi HR (2021) Landslide susceptibility mapping using machine learning algorithms and comparison of their performance at Abha Basin, Asir Region, Saudi Arabia. Geosci Front 12:639–655. https://doi.org/10.1016/j.gsf.2020.05.010

Zeidan BA (2015) Combined Seepage and Slope Stability Analysis of Reservoir Earth Dams. Fac Eng Tanta Univ

Zeqiri RR, Riheb H, Karim Z, et al (2019) Analysis of safety factor of security plates in the mine" Trepça" Stantërg. Min Sci 26:21

Zhang W gang, Meng F sheng, Chen F yong, Liu H long (2021) Effects of spatial variability of weak layer and seismic randomness on rock slope stability and reliability analysis. Soil Dyn Earthq Eng 146:106735. https://doi.org/10.1016/j.soildyn.2021.106735

Zheng Y, Chen C, Liu T, et al (2019) Stability analysis of anti-dip bedding rock slopes locally reinforced by rock bolts. Eng Geol 251:228–240. https://doi.org/10.1016/j.enggeo.2019.02.002

Zheng Y, Tang X, Zhao S, et al (2009) Strength reduction and step-loading finite element approaches in geotechnical engineering. J Rock Mech Geotech Eng 1:21–30

Zhou J, Wang J (2017) Lower bound limit analysis of wedge stability using block element method. Comput Geotech 86:120–128

Zienkiewicz OC, Humpheson C, Lewis RW (1975) Associated and non-associated visco-plasticity and plasticity in soil mechanics. Geotechnique 25:671–689