



## A Review Study for Rock Slope Stability Assessments and Stabilization Methods

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### ABSTRACT

Slope stability of rock structures considered as the most important field in rock mechanics. Stability analysis of the jointed rock slopes are evolved during many years. The different methods are developed to understand and analysis various rock failures and describe sliding mechanism. The rock engineering experts in this field have provided significant achievements in terms of stability analysis and monitoring in jointed rock slopes and introduced extensive stability analysis and stabilization methods. The presented study is tried to prepare a review study on several works conducted on rock slope stability and stabilizations. In this regard, while examining the structured analysis of the stability of rocky slopes, some of the most important achievements in this field have been considered.

### 1. Introduction

Slope stability analysis identified as analytical, empirical, or computer-based evaluation of the stability for slope which is covers earth-fill/rock-fill dams, embankments, excavated slopes, open-pit mines, and natural slopes regarding static or dynamic loadings (Zahri et al., 2016; Azarafza et al., 2017a; Li et al., 2020; Kumar et al., 2021). In fact the stability analysis of the slopes refers to the condition of rock mass to undergo movement and failure of the rock body occurred (Huang, 2014). The stability condition of rock slopes are subject of study and research in geotechnical engineering and engineering geology (Michalowski and Drescher, 2009) which generally aimed at understanding the mechanism, moods, type and causes of an occurred slope failure (Saadoun et al., 2020) or the factors involved the failure occurrence and

trigger rock slope movements (Turanboy et al., 2018). Nevertheless, the stability assessments of the slopes are controlled by passive shear strength and the acting shear stress ration which mostly named as safety factor (F.S or SF). The safety factor term is mostly used in analytical and empirical assessments which are represent the degree of reliability for rock mass regarding to the structural failures (Wyllie and Mah, 2004). A slope can be mainly stable if the safety factor were computed along any potential sliding surface started from the top of to the toe, is always larger than 1 ( $F.S > 1.0$ ). The stand of 1 in safety factor is considered as critical status which is required the attentions, modification and stabilizations. On the other hand, the smallest value of the safety factor ( $F.S < 1.0$ ) will be considered as representing the main instability condition of the slope. In such situation it is required to immediately stabilizations (Huang, 2014). Similarly, a slope can be locally instable if a safety factor less than 1 in part of slope

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surface (shallow sliding) which globally slope still stable. In such circumstances the sliding surface running through a limited deep in slope's surface which is not grown into the slope's body (Li et al., 2020). However, the safety factor is an index evolution for demonstrate the condition of the stability in slope. In applied work and geotechnical tasks this factor is typically is comprised between 1 and 1.3, depending on regulations which is indicate marginally stable slopes that require attention, monitoring and/or an engineering intervention to increase the safety factor and reduce the probability of a slope movement (Hou et al., 2019).

During a time, several methods are developed to investigate the rock slope stability analysis which can categorized from simple wedge, planar strain, limit state, kinematic, limit equilibrium, numerical and hybrid methods (Fredj et al., 2020). In the meantime, limit state, kinematic, limit equilibrium, and numerical methods has received considerable attentions form the scholars past the time (Paparo, 2014).

*Limit state analysis:* The limit analysis is rigorous approach to slope stability analysis in rock slope engineering. Unlike limit equilibrium, the limit analysis is based on rigorous plasticity theory. This enables, among other things, the computation of upper and lower bounds on the true factor of safety. There several programs were used limit state analysis of evaluate the slopes stability conditions which can classify as OptumG2, and LimitStateGEO. The General purpose of such geotechnical software application based on discontinuity layout optimization for plane strain problems including slope stability.

*Kinematic analysis:* the kinematical analysis examines which modes of failure can possibly occur in the rock mass. The stability analysis requires the detailed evaluation of rock mass structure and the geometry of existing discontinuities contributing to block instability (Qin and Chian, 2018). Stereonets of the planes and lines is used which are useful for analyzing jointed rock blocks regarding rock slopes were divided the rock mass into the various rock blocks. The DIPS software is the common program used based on stereonet for visualization of structural data regarding the jointed rock mass to determine of the kinematic feasibility of rock mass and statistical analysis of the discontinuity properties (Paparo, 2014). The other program was used basically kinematic analysis for simulators of rockfall are the Rockfall program. Rock slope stability analysis may design protective measures near or around structures endangered by the falling blocks which determine travel paths and trajectories of unstable blocks separated from a rock slope face. Calculation requires two restitution coefficients that depend on fragment shape, slope surface roughness, momentum and deformational properties and on the chance of certain conditions in a given impact (Qin and Chian, 2018).

*Limit equilibrium analysis:* The limit equilibrium is one of the most fundamental basic analytical methods for jointed rock slope stability assessments which that are used

in slope stability studies because of their simplicity, low complexity in the formulation, and less time's for analysis. The limit equilibrium method is classified on massive analysis or slices procedures which is investigate the possible surface for sliding in the slope. The evaluation process concluded the forces or moments balance for the movable mass above the principle rock joints (Yamaguchi et al., 2018). The safety factor is playing an important in slope stability analysis regarding to the limit equilibrium methods. The safety factor is evaluated for different type of the slope sliding form the rock mass. Rock slope stability analysis based on limit equilibrium techniques may consider following modes of failures (Wyllie and Mah, 2004):

- Planar failure: The rock mass sliding is occurred on a single surface of the basic joint; the two-dimensional assessment may be use a concept of blocks resisting on an inclined plane at limit equilibrium circumstances.
- Massive failure: the rock mass sliding is usually takes place on polygonal-shaped active surfaces that calculated based on several assumptions. The assumptions mostly covered the rock mass condition and jointed network on the rock mass. In massive movements, the sliding mass is composed from multi-shape particles which are kinematically possible to move under internal shear surfaces. So, the rock mass is divided into blocks by internal shear surfaces and no tensile strength is permitted etc.
- Wedge failure: the wedge instability is one of the most common failure types in rock slopes were occurs based on the wedge shape mass movements along the intersection of the two main joints in rock slope. The computer-based analysis enables modeling of the wedge sliding on two planes in a direction along the line of intersection.
- Toppling failure: Long thin rock columns formed by the steeply dipping joints networks rotate about a pivot point located at the lowest corner of the block. The moments causing toppling of rock block. On the other word, the toppling is occurs in rock slopes where the acting joints orientation close to the vertical and opposite of the slope face orientation.

*Numerical methods:* Numerical modeling is providing an approximate solution to solve the complex problems which can be answered by close-form solutions. Numerical analysis methods are allows to deformation of materials and failure occurs during dynamic loading, creep deformation, water pore-pressure, etc. However, numerical modeling is restricted by some limitations and based on the operation conditions (continuum or discontinuum environments), required to consider several assumptions. For example, input parameters are not usually measured and availability of these data is generally poor. User also should be aware of boundary effects, meshing errors, hardware memory, and time restrictions (Zhang et al., 2012). In rock engineering especially rock slope stability

analysis discontinuum methods such as discrete element modeling (DEM) technology and universal distinct element code (UDEC) software. UDEC is exclusively developed to cover the numerical analysis for jointed rock mass and obtained stability condition base on the jointed network in rock mass.

## 2. Failure Types in Slope Instabilities

According to the various empirical and analytical task conducted on rock slope stabilities, there are various stabilization methods are performed for the modified different type of the slope failures. The stabilization methods can be classified in geo-material-based and structural-based modifications (Huang, 2014) were required the specific conditions of rock slope failure and ground. Nevertheless, there are several types of the rock slope failures which lead to global instabilities which is detailed describe as follow:

*Planar failure:* this type of the failure is occurred on a flat joint which considered as special forms of wedge failure were rock mass is moved along with the joint plane. Fig. 1 is provided the geometrical scheme of the planar failure in rock slope (Wyllie and Mah, 2004).

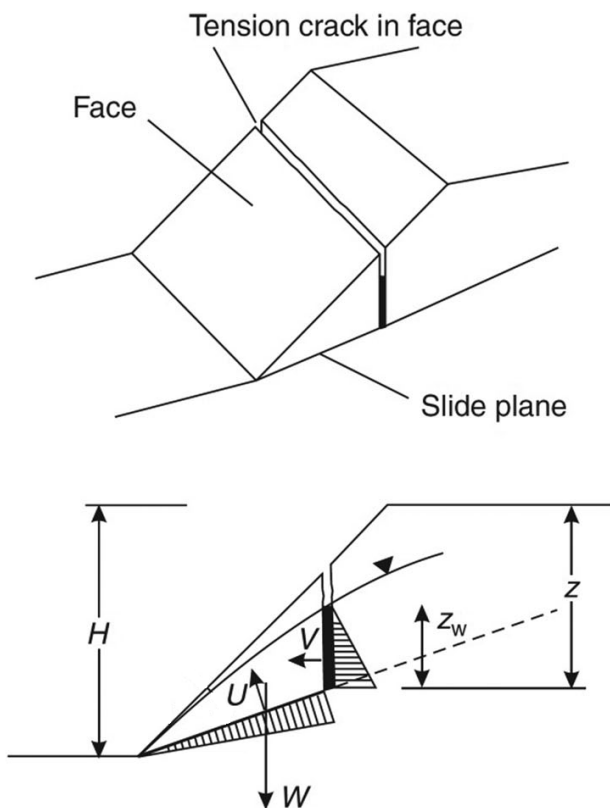


Figure 1. The general scheme of the planar failure in rock slopes (Wyllie and Mah, 2004)

*Wedge failure:* The wedge failure is a common failure mood in rock slopes which is occurred in specific geometry and geological conditions. The failure is started regarding the principle two joints that responsible the movements of rock blocks downward of slope. The wedge failure is a three-dimensional instability were analysis in two-dimensional space as same as planar failures, but in-fact the basic joint is an intersection of two main joints' planes. Fig. 2 is provided the geometrical scheme of the wedge failure in rock slope. As seen in this figure, the several parameters are involve the wedge instability in rock slopes, these parameters can be classified in joints network, slope angle, the intersection tilt and rock blocks geomechanical properties (Wyllie and Mah, 2004).

*Massive failure:* the massive failure which is known as rotational failure, spherical failure or circular failure is a oldest type of the failures are detected by scholars and experts during the slope's instability which is very common in soil mass and heavy jointed rock slopes. The massive failure is mostly followed the complex failure surface during the ground movements which is not possible to estimate the sliding potential surface by one or several joint sets. So, the sliding surface generally passes through the materials and joints and generates the circular or semi-circular shapes (USACE, 2003). Fig. 3 is provided the geometrical scheme of the massive failure in rock slope.

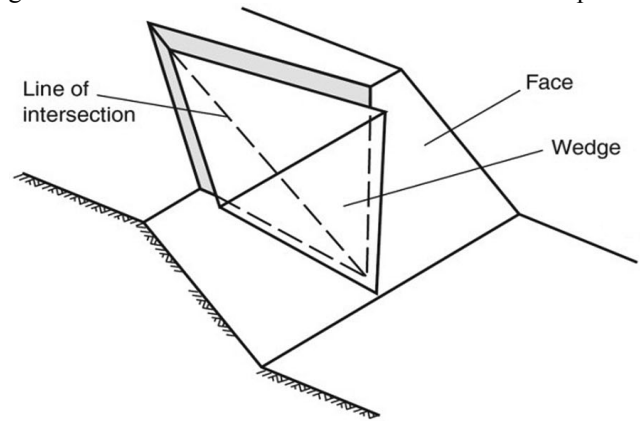


Figure 2. The general scheme of the wedge failure in rock slopes (Wyllie and Mah, 2004)

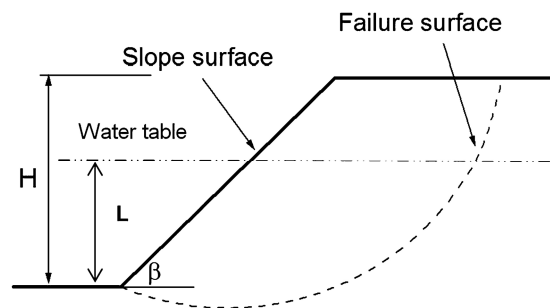


Figure 3. The general scheme of the massive failure in rock slopes (Wyllie and Mah, 2004)

Regarding to the studies conducted on the massive failure, it can be stated that the oldest calculation process related to this type of the slope stability assessments which is back to Fellenius (1936) works. Fellenius (1936) is use the Fellenius method (known as ordinary method of slice) which is compressively used for hand-writing calculation for slope stability. The well-known method is use moment equilibrium about the circle center for soil slope (or heavy jointed rock mass) under massive failure to evaluate the safety factor. Bishop (1955), Janbu (1954), Nonveiller (1965), Sarma (1979), and Morgenstern and Price (1965) use the basics of the Fellenius method to develop more complicate method to understand the circular failures which is used in different programs such as GeoStudio software.

*Toppling failure:* The toppling is considered as one of the most complicated failures occurred in rock slopes. The topping is composed from the rock blocks overturn and fall around a point in the base without sliding. The main causes of the topping are related to the geological complexities which leads to occurred different type of topple failure in rock slopes (Nikoobakht and Azarafza, 2016). Ashby (1971) is introduced the toppling a rock blocks overturn as a first scholar, but Goodman and Bray (1976) is provide the principle classification system for toppling based on failure mechanisms. The scholars present the primary and secondary toppling classification which considered various type of the toppling. The primary group is containing flexural failure, block failure, and block-flexural failures (Gu and Huang, 2016). The secondary group is consisting of wide range of the toppling related to geological complex condition of the slopes. The most frequent of secondary is concluded joint-slip, anti-inclined, foot-wall, head-topple, toe-topple, ploughing-slab, columns-lateral fall, pit-crest, hinge-buckling, and euler-buckling (Alejano et al., 2010, 2011; Havaej et al., 2014; Sun et al., 2020, Azarafza et al., 2021). Generally the primary group of the toppling failures is more common than secondary group. The primary group is studied by several scholars and reported various cases worldwide (Amini et al., 2009). However, there are several calculation procedures to estimate the stability condition of the toppling in rock slopes which is classified in analytical, numerical and empirical methods (Azarafza et al., 2020a; 2020b). Fig. 4 is provided the geometrical scheme of the primary toppling failure in rock slopes.

*Composite failure:* The composite failure which is known as complex movement is earth failure in different scale sliding with various geo-materials. In such instabilities the sliding surface mostly complex and formed in multiple location on the slope. The rocky materials can be combined with soils, mud, submerged particles, etc. the general concept for the composite failures is landslide (if the scale of the failures is large and regional). The mechanism of the composite failures can be above items alone or in combination (Highland and Bobrowsky, 2008). Fig. 5 is provided the examples for different type of the rock slope instabilities regarding to the failure types.

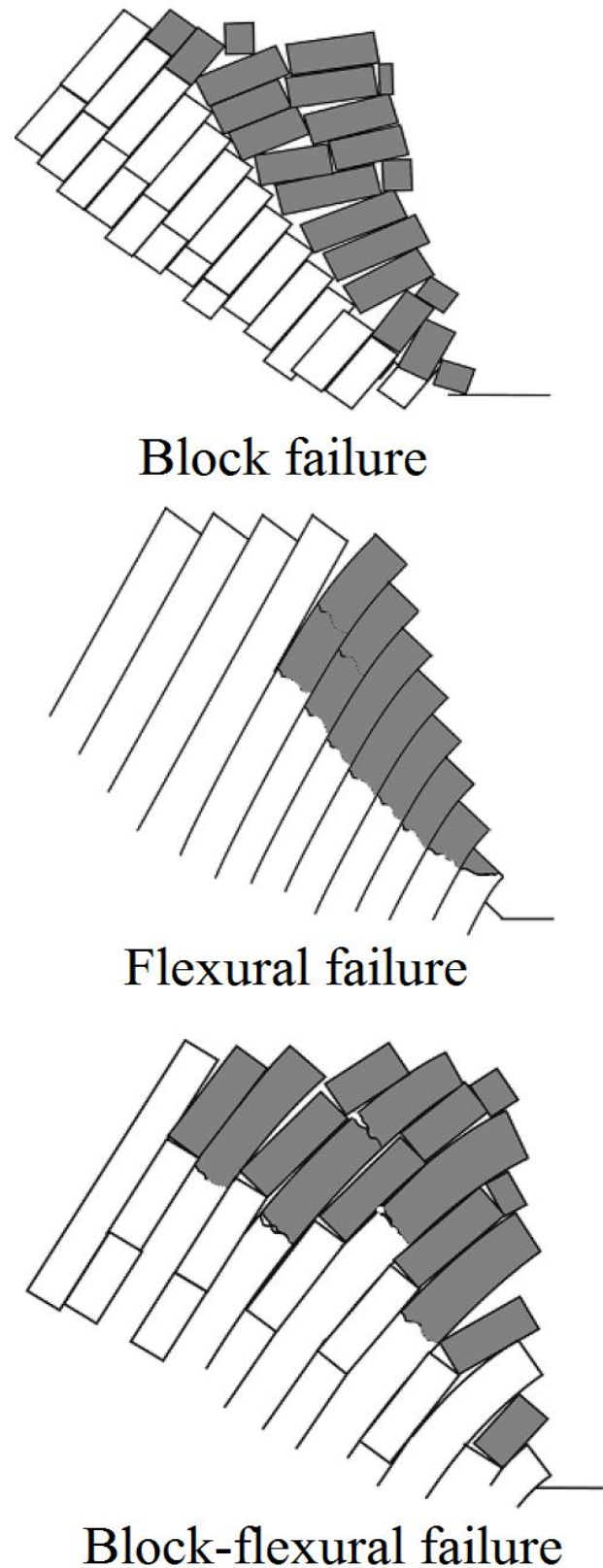


Figure 4. The general scheme of the primary toppling failure in rock slopes (Amini et al., 2012)



Figure 5. The topic examples for different type of the failures occurred in rock slopes (Source: Internet/Google-image)

### 3. Rock Slopes Stabilizations

In many slope stabilization cases, geo-engineers use engineering procedures to stabilize the risk-able rock slope during long-term viability and reduce localized slope failure regarding to the failure mechanism, geological process, erosion, weathering, man-works, etc. Generally, there are two large groups of the stabilization procedures. These effective strategies are to prevent the failure regarding to the install structures and slope improvements to protect the slope against them in the future. There are many methods that can be used to stabilize a rock slopes from sliding. The most common methods include altering the slope geometry, installing drainage, adding reinforcement, or a using combinations of these methods (FHWA, 2012). Each of these methods required the specific procedure to implement the stabilizations (Abramson et al., 2001). The professionals classified the stabilization methods into the decrease driving force (change geometry, lower groundwater), increase resisting force (change geometry, lower groundwater, increase shear strength of slope mass, drainages), surface protection (reinforcements), ground improvement (grouting, cement stabilization, chemicals), and column supported embankments (retaining walls, beams, shotcrete, pile walls, bolts) which considered for different types of the slopes which various failure conditions (FHWA, 2012). In the meantime, the geometrical alterations and structural installations for rock slopes are received attentions from experts. These methods are change the configuration of a slope by removing rock blocks during scaling (hand, mechanical or blast) process. Scaling is the technical process of removing loose or potentially unstable rock blocks from slope mass that might affects the trajectory of falling rock and leads to local instabilities. Scaling is effective on natural and excavated slopes and is done as periodic maintenance for any slopes that pose a potential rock sliding to road-ways (Waltham, 2009). For scaling, the hand tools and/or mechanical equipment are used to remove loose rock and transfer from the slope which is temporary required for repaired every 2 to 10 years (Abramson et al., 2001). The blasting is generally used in open-pit mine or mining operations which is not nearing to the cities or infrastructural facilities. This method uses to remove overhanging faces and protruding knobs and to modify the slope angle and slope stability (FHWA, 2012).

There are several installations or structural stabilization procedures were conducted to provide the stability condition of the rock slopes which can uses in debris containment, difficulty with drilling, and undermining (Abramson et al., 2001). In such stabilizations using both internal and external stabilization can provide more efficient actions. Rock bolts, dowels, shear pins, inject-able resins or epoxies, are the most common internal stabilizations were used in rock slope modifications. Shotcrete, drainages, walls, meshes are categorized in external stabilization (Waltham, 2009).

However, the various stabilization methods was used for improve the stability condition of rock slopes. Each of these procedures needs to conduct the extensive field survey and geotechnical investigation to recommend efficient method of stabilization (Azarafza and Asghari-Kaljahi, 2016).

### 4. Conclusion

The presented study attempted to provide a review article on rock slope stability and stabilization procedures. In this regard, the most effective methods in jointed rock slope stability are considered. The rock slope failures are categorized and developed methods to estimate the instabilities conditions are illustrated. As outlook of the rock slopes failures such as massive failure, planar failure, wedge failure, toppling failure and composited failure are discuss and stabilization methods for these instabilities are recommended.

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