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Assessing Rock Slope stability using Empirical, Kinematic and Numerical analysis

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Abstract

The slope stability evaluation of rock slopes becomes essential and critical for assessing the safe design of excavated cut slopes and/or the equilibrium condition of the natural slopes due to the multiple factors that contribute to instability. Presently, a vast range of slope stability methods and approaches are available for both rock and mixed rock -soil slopes. The stability of slope depends on slope geometry, rock mass properties, weathering grade and discontinuities. This paper aims to evaluate the slope stability of a tunnel portal slope in India through a comprehensive approach that integrates empirical methods, kinematic analysis, and numerical analysis to recommend an efficient slope support system. Preliminary assessment of slope stability is carried out using slope mass rating (SMR) as an empirical method. Kinematic analysis based on the joint sets to identify potential failure modes is performed in Dips software. The stability of wedges is checked for planar and wedge failures in RocPlane and SWedge tools respectively. Further numerical analysis is carried out in RS2, a finite element software to find critical factor of safety using shear strength reduction approach and a competent support system is recommended to cater all the modes of failure. This integrated approach demonstrates that while empirical method is useful for initial evaluations, a comprehensive stability analysis requires detailed insights from kinematic, and numerical analyses. This study highlights the advantages of a multi-faceted approach in accurately assessing slope stability and effective design of slope support.

Keywords

Rock slope, Slope mass rating (SMR), Kinematic analysis, Dips, RocPlane, SWedge, Shear strength reduction, slope support.

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1 Introduction

In emerging countries like India, the development of infrastructure projects such as high-speed or rapid rail network plays a crucial role in enhancing connectivity and regional development. As these large infrastructure projects often extends through diverse and challenging terrains, including mountainous regions where they pose significant engineering challenges. Slope stability particularly in rocks is one of the primary challenges, as failure can lead to catastrophic consequences, including landslides, damage to infrastructure, and potential loss of life. Therefore, a thorough understanding of slope stability and implementing effective stabilization measure is essential to ensuring the safety of slopes in these terrains and maintaining long term sustainability of the infrastructure.

Rock slope stability has been extensively studied through various methods including empirical, kinematic and numerical analysis. While empirical methods provide quick evaluations, kinematic analysis examines the failure caused by geological discontinuities and numerical methods are used for circular failures which incorporate rock mass strength and in situ stress conditions. A single method often fails to account for all the variables affecting slope stability such as complex geology, discontinuities and rock mass strength. Hence, combined empirical, kinematic and numerical analyses provides a more comprehensive and accurate assessment.

This study focuses on a portal slope of a tunnel passing through mountainous region in India, using an integrated methodology such as empirical, kinematic and numerical analysis to evaluate slope stability and recommend optimal support system.

2 Geology and Geometry

2.1 Geology of study area

The mountainous region at the slope site comprises Basaltic rock formations, which dominate the geological profile of the area. Based on detailed geological surface mapping three distinct joint sets have been identified within the rock mass. The specific characteristics of these joint sets, such as orientation, dip angle and joint shear strength are summarized in Table 1, providing the crucial data for kinematic analysis of the slope.

Table 1 Joint sets and their characteristics

Joint set	Dip (degree)	Dip direction (degree)	Cohesion (kPa)	Angle of internal friction (deg.)
J1	70	5	50	20
J2	70	210	50	20
J3	65	265	50	20

To further understand the subsurface conditions, a borehole drilled at site location is referred. The borehole stratigraphy reveals an upper layer of approximately 2 meters of gravel, followed by various weathering grades of Basaltic rock below. The geotechnical properties of both the soil and the rock mass have been meticulously evaluated and detailed in Table 2 and Table 3.

Table 2 Shear strength parameters of soil

Depth (m)	Soil type	c (kPa)	ϕ (deg.)	E (MPa)
0-2	Gravel	-	34	55

Table 3 Rock mass parameters

Depth (m)	Rock type	ϒ, (kN/m^3)	σ_{ci}, UCS (MPa)	GSI
2-5	Completely weathered Basalt (Grade V)	27	14.14	20
5-13	Moderately weathered Basalt (Grade III)	27	66.31	57
>13	Slightly weathered Basalt (Grade II)	27	92.40	70

2.2 Geometry of cut slopes

This study focuses on a railway tunnel portal cut slopes located in a mountainous region of India. Due to the requirements and restricted site conditions, the cut slopes mandated to be excavated at a steep inclination of 1V :0.2H (79°).

- Slope Face 1 corresponds to the cut slope through which tunnel alignment passes, oriented at N 340°.
- Slope Face 2 and 3 represents the transverse slopes at tunnel portal oriented at N 250° and N 70° respectively.

The geometry of cut slopes with orientation of all slope faces is depicted in Fig. 1.

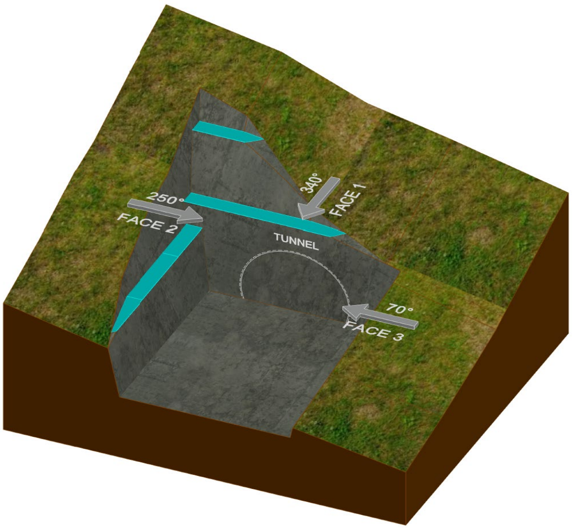

Fig. 1 Geometry of the cut slopes

3 Failures in Rock slopes

Unlike in soils, slopes in rocks fail due to presence of discontinuities or joints within the rock mass, which weaken its structural integrity. These joint induced failures include planar wedge and toppling failure, each characterized by the orientation and interaction of the joints relative to the slope face and the stress field. Understanding these types of failure is critical for slope stability analysis in rock engineering, particularly in projects like tunnels, high-speed rail construction, and open-pit mining. This section deals with the types of failures in rock slopes and causes for different slope failures.

3.1 Planar failure

Planar failure, also known as sliding failure, occurs when a single plane or discontinuity in the rock mass aligns closely with the slope face and dips in the same direction. Key conditions for planar failure are:

- The plane or discontinuity has an inclination angle less than the slope face but greater than the angle of internal friction.
- The joint or discontinuity moves outside (within approximately ±20°) thr face of the slope.

3.2 Wedge Failure

Wedge failure occurs when two or more intersecting joints form a wedge-shaped block of rock that is susceptible to sliding. For wedge failure to occur:

- The intersection line (or trend) of the two joint planes must dip out of the slope face.
- The plunge of the line must be flatter than the slope face and higher than the angle of internal friction.

3.3 Toppling failure

Toppling failure involves the forward rotation and overturning of blocks or columns of rock. It typically occurs when:

- The joint or discontinuity moves into (within approximately ±10°) of face of the slope.
- $(90°-\psi f)+ \phi j < \psi p$, given by Goodman and Bray, 1976. Where ψf is cut slope angle, ϕj is friction angle and ψp is dip of joint.

3.4 Circular failure

Planar, wedge and toppling failures in rock slopes governed by joints or discontinuities in rock mass. However, in case of a closely fractured or highly weathered rock, a strongly defined structural pattern no longer exists, and the slide surface is free to find the line of least resistance through the slope. Observations of slope failures in these materials suggest that this slide surface generally takes the form of a circle.

The conditions under which circular failure will occur arise when the individual particles in a soil or rock mass are very small compared with the size of the slope. Hence, broken rock in a fill will tend to behave as a "soil" and fail in a circular mode when the slope dimensions are substantially greater than the dimensions of the rock fragments.

4 Methodology

This study utilizes a comprehensive multi-method approach to evaluate the stability of rock slopes combining Empirical, Kinematic and numerical analysis.

4.1 Empirical method

Slope Mass Rating (SMR) is used for preliminary assessment of the stability of rock slopes as an empirical method. It is an adaptation of Rock mass rating (RMR), originally developed by Bieniawski but modified to account for the orientation of discontinuities in relation to the slope face. The slope mass rating (SMR) is calculated as Eq. 1.

$$\text{Slope mass rating (SMR)} = \text{RMR}_{\text{basic}} + (F1 \times F2 \times F3) + F4 \qquad (1)$$

Where *F1* is dependent on parallelism between the slope and the discontinuity.
F2 is dependent on the dip of discontinuity.
F3 dependent on the relationship between discontinuity and inclination of slope.
F4 dependent on method of excavation (value of zero corresponding to blasting considered in the present analysis)

4.2 Kinematic analysis

Kinematic analysis identifies the potential failure mechanisms by evaluating the orientation of joint sets with respect to the slope face. This study uses Dips software to visualize and analyse joint planes, assessing their likelihood to form planar, wedge, or toppling failures. The RocPlane and SWedge tools are used to further investigate planar and wedge failures, respectively.

4.3 Numerical analysis

For more detailed and reliable assessment, numerical analysis is carried out in a finite element software (RS2) using shear strength reduction (SSR) technique. SSR technique involves systematically reducing the shear strength parameters of the rock within a slope until failure occurs. The goal of the SSR technique is to determine the factor of safety (FOS) of a slope, which indicates how close the slope is to failure under existing conditions.

5 Results and Discussions

5.1 Empirical method - Slope Mass rating (SMR)

The average Rock mass rating (RMR) of the slope, as determined from the geotechnical investigation is found to be 41. Slope mass rating (SMR) is calculated for all the three slope faces considering all the joint sets encountered. The calculated SMR values for three slope faces are tabulated in Table 4.

Table 4 SMR of the slope faces

Joint set	RMR_{basic}	SMR (Planar)			SMR (Toppling)		
		Face 1	Face 2	Face 3	Face 1	Face 2	Face 3
J1	41	34	34	34	37	37	37
J2	41	34	34	34	37	37	37
J3	41	32	-1	32	37	37	24

Based on slope mass rating (SMR), it is concluded that slope of 1V:0.2H would require systematic important corrective measures to attain stability during excavation. Systematic supports are recommended for slopes since joints are likely to cause planar and toppling failures to occur. Hence these cases will be further analysed.

For face 2, J3 incites more vulnerability to make the slope unstable. Important corrective measures by also providing proper drainage arrangements are recommended to attain stability during excavation.

SMR method has got limitations, as it does not consider height of the excavation and material properties. So proper conclusions regarding the slope stability would be arrived after detailed kinematic and numerical analysis.

5.2 Kinematic Analysis

Kinematic analysis has been performed in Dips software for all the three slope faces considering all the joint sets present in the rock mass. A typical planar and wedge failures observed for Face 2 when interacting with all joints are shown in Fig. 2 and Fig. 3. The analysis results summarizing the identified failure modes in each slope face is provided in Table 5.

Table 5 Interpreted modes of failures from Kinematic analysis

Face	Planar failure	Wedge failure	Toppling failure
Face 1	-	J1 & J2 J1 & J3	-
Face 2	J3	J1 & J2 J1 & J3 J2 & J3	-
Face 3	-	-	-

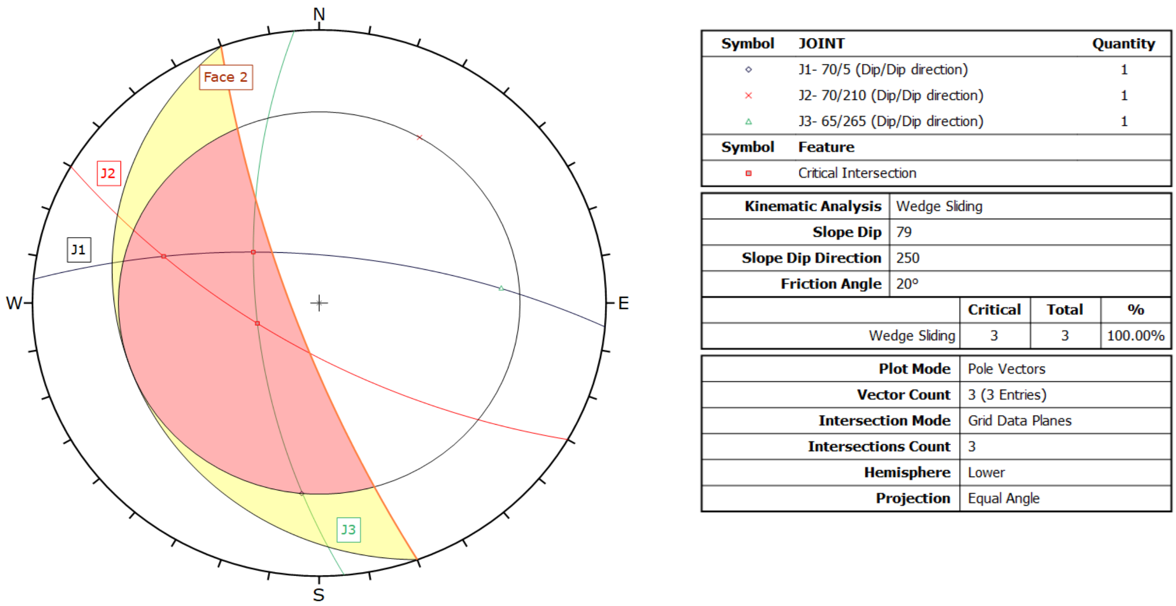

Fig. 2 Kinematic Analysis of Face 2 for Planar failure

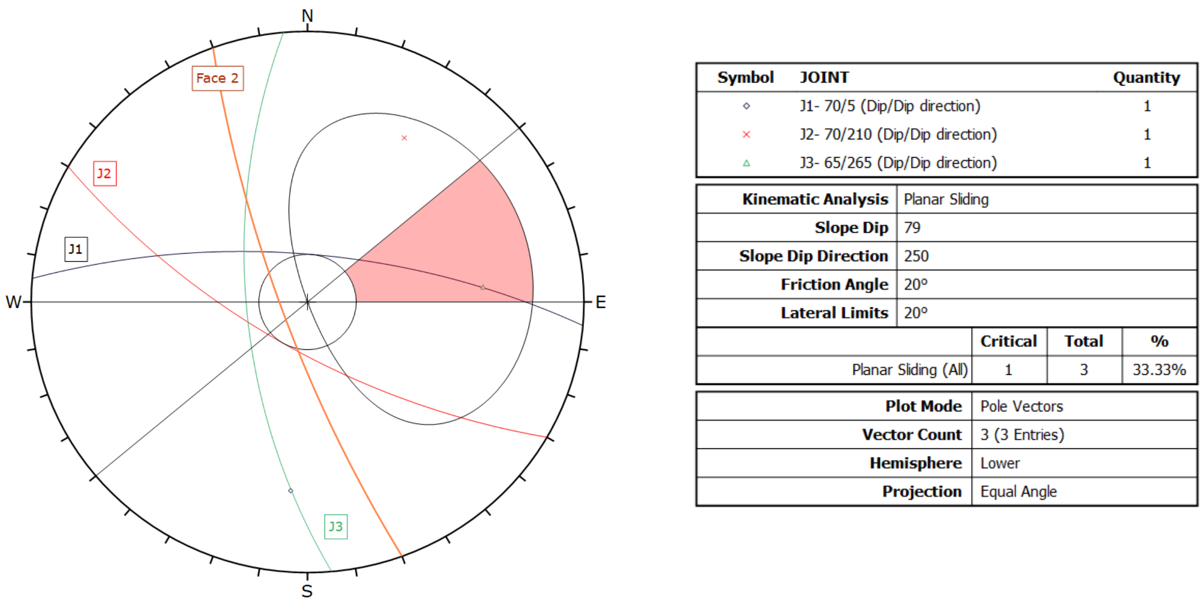

Fig. 3 Kinematic Analysis of Face 2 for Wedge failure

The results of the kinematic analysis suggest that the planar and wedge failures identified are likely to lead to instability in the slope. To access these failure modes in more detail, planar and wedge stability analysis is conducted using RocPlane and SWedge respectively. To mitigate the risk of these failures, rock bolts of 6m length @ 2m c/c spacing are installed as a stabilizing measure. The analysis is performed under both unsupported and supported conditions and shown in Fig. 4. The analysis results for planar and wedge stability are given in Table 6 and Table 7.

Table 6 Planar analysis results in RocPlane

Face	Joint set	Unsupported FOS	Supported FOS
Face 1	J3	0	3.21

From the analysis it is inferred that, the planar failure causing by J3 is found to be safe with the recommended support system of systematic rock bolting.

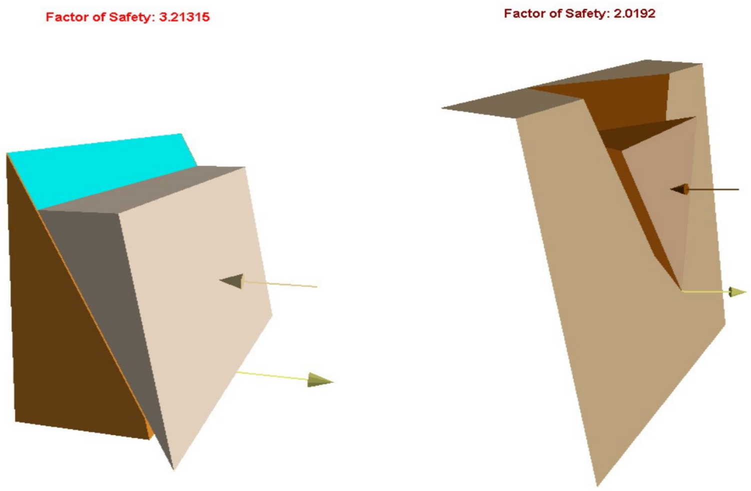

Fig. 4 Stability of Planar and Wedge failures after support

Table 7 Wedge analysis results in SWedge

Face	Joint set	Unsupported FOS	Supported FOS
Face 1	J1 & J2	13.54	17.51
	J1 & J3	0.0	2.01
Face 2	J1 & J2	17.52	22.60
	J1 & J3	0.0	2.43
	J2 & J3	0.0	1.94

The wedge stability analysis results indicates that the wedges formed by the intersections of joint sets J1 and J2 in both slope faces are stable without any support. However, the other wedges formed by intersections of J1 & J3 in both the slope faces and J2 & J3 in slope face 2 are unstable in unsupported condition. As a result, systematic rock bolts are required to prevent failure from these wedges. However, kinematic analysis focuses purely on the geometry of slopes and does not account stress analysis and strength of rock mass which can further analysed using numerical analysis.

5.3 Numerical analysis

To validate the support system designed by Planar and wedge analysis, numerical analysis is carried out in RS2 a finite element software using SSR technique for all the three faces. Systematic rock bolts as given in planar and wedge analysis along with 100mm shotcrete with wire mesh to control the displacements are provided. The cut slopes modelled in RS2 for all the three slope faces are shown in Fig. 5. The stability of slope faces is assessed by evaluating the Factor of Safety (FoS) against shear failure and also analysing the stresses acting on the supporting rock bolts, as shown in Fig. 6 and Fig. 7. The resulted FoS for slope faces is provided in Table 8.

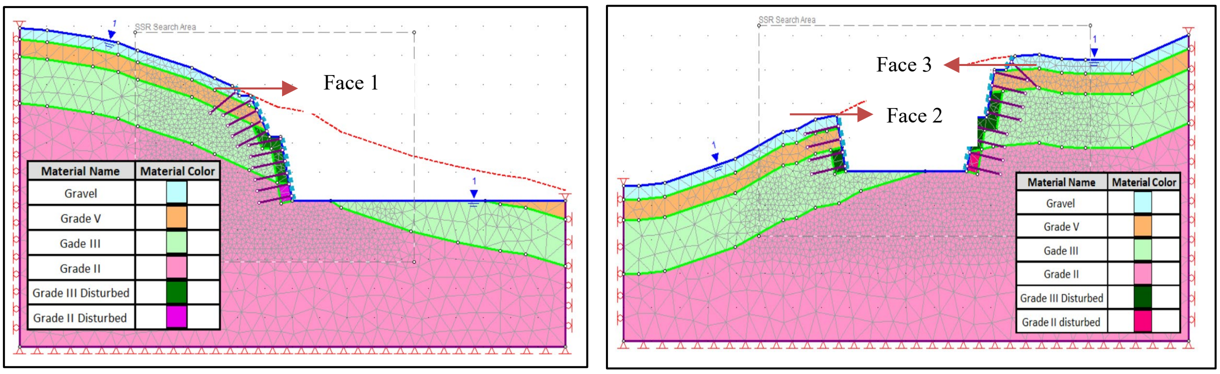

Fig. 5 RS2 model of cut slopes (Face slope & Transverse slopes)

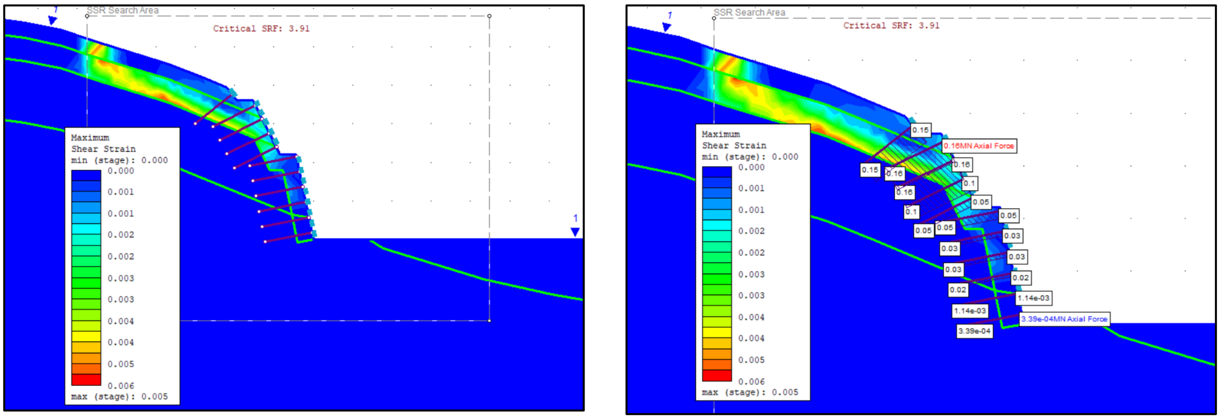

Fig. 6 Tunnel Face slope (Face 1) numerical analysis results – Shear strain & Bolt forces

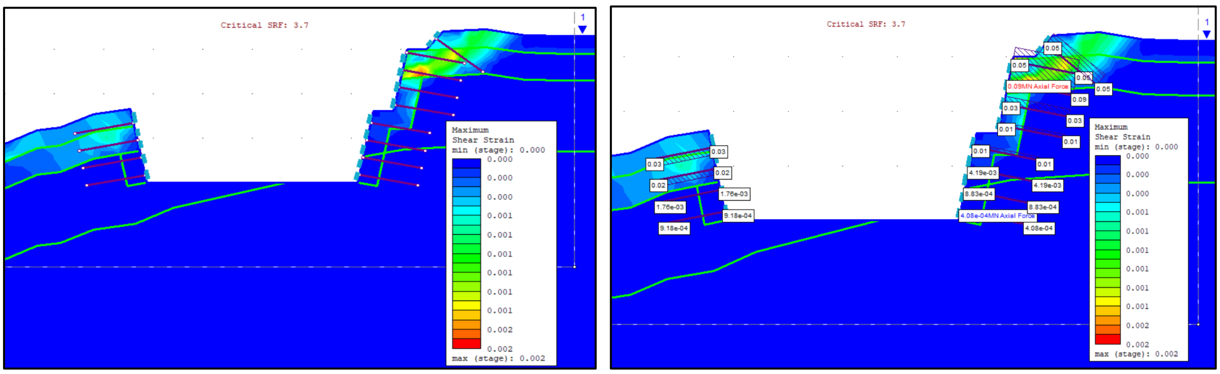

Fig. 7 Tunnel Side slopes (Face 2 & Face 3) numerical analysis results – Shear strain & Bolt forces

Table 8 Factor safety from RS2 analysis

Face	Factor of safety
Face 1	3.91
Face 2 & 3	3.70

The results of numerical analysis indicate that the provided support system yields the factor of safety higher than the required value for stability. Hence, the support system effectively stabilizes the slope, providing a greater margin of safety against circular failure.

Also, the higher factor of safety demonstrates the slope is adequately reinforced to prevent all the modes of failures during and post excavation

6 Observations and Conclusions

This study assessed the stability of a rock slope using various approaches and the following key observations and conclusions were drawn.

- Implementing empirical method by estimating SMR value of slope as a preliminary assessment, it identified the need for support to attain stability due to joints interaction.
- But SMR method has got limitations, as it does not consider height of the excavation and material properties which can be checked completely using kinematic and numerical analyses.
- Potential formation of planar and wedge failures along the slopes is identified by Kinematic analysis of slopes.
- Considering joints interaction with portal slope, kinematic analysis plays an important role to identify critical joint sets like J3 as observed from Table 5 and Table 6.
- For estimating factor of safety against circular failure, finite element numerical analysis (RS2 software) is used incorporating the in-situ conditions of the slope and by providing the support system the slope is stable with a factor of safety of 3.91 and 3.70 as given in Table 8.
- The rock bolts provided along the slope are checked for stresses and found they are under the design capacity.
- Hence, this comprehensive approach for designing rock portal slopes will ensure stability for all the possible failures

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