International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 07 Issue: 05 | May - 2023 Impact Factor: 8.176 ISSN: 2582-3930

Slope Stability Analysis under Different Loading Conditions using a Numerical Method (FLAC/Slope 2D)

Lily Gurung[1], Manoj Chhetri[2]

[1]Civil Engineering Department, College of Science and Technology, Royal University of Bhutan
[2]Information Technology Department, College of Science and Technology, Royal University of Bhutan

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Abstract

Slope stability analysis is a very important phenomenon which can prove to be significantly relevant for tectonically active regions and the Himalayas. There are various methods that can be adopted to analyze the stability of a soil or rock slope. Some of the methods include the limit equilibrium methods and numerical methods, where one can model the slopes case wise and draw conclusions. Following the background study and thorough literature review, the current study focusses only on the numerical modelling and analysis of a weathered slope, as the numerical methods are more advantageous than the traditional methods. FLAC/Slope 2D is used to model 5 different case wise models to carry out the slope stability analysis, which employs finite difference method and shear strength reduction technique to calculate the factor of safety (FoS) of a given model. Conclusively, after modelling and analysing various cases, it was found that the weathered rock slope with complex geometry subjected to forces like pseudostatic force in the presence of water table have FoS lesser than unity, which is unsafe. However, with the introduction of reinforcements along the slope as mitigative measure, the stability of the given rock slope increases by 45.5% to 49.3%.

Key Words: slope stability analysis, numerical modelling, finite difference method, FLAC/Slope 2D, factor of safety

1. INTRODUCTION

Assessment of the stability of a slope is a challenging as well as an important element of engineering works like dams, embankments, highway or road constructions. Generally, limit equilibrium methods (LEMs) are employed to evaluate the slope stability encompassing the shear strength and shear stress components. While others include finite difference methods (FDMs), finite element methods (FEMs) and empirical techniques like slope mass rating (SMR) for rock slopes. As a result of the evaluation process using any of the methods, a factor of safety (FoS) is determined by obtaining the quotient of the resistance offered by the slope to the driving forces. Normally, a FoS greater than 1 implies that the slope under analysis is stable.

Slope stability analysis is a very important phenomenon especially for regions which are tectonically active and also at the places where there are presence of weathered rocks and rock masses. Although LEMs are commonly used over decades, it can be inadequate and has the limitation to provide evident analysis for complex slopes and their failure mechanisms. Whereas numerical methods are especially useful when the slopes are subjected to different loading conditions and complex slope geometries. Therefore, after vigorous literature review and of various researchers, the aim of the current research is to model and analyze the slopes of complex geometry with various parametric conditions by using the numerical modelling software known as FLAC 2D (Fast Langrangian Analysis and Continua). FLAC 2D applies finite difference method (FDM) to do the slope stability analysis.

2. Literature Review

Dawson and Roth (2000) studied the slope stability analysis using FLAC. According to them, a slope's FoS can be calculated using FLAC by gradually lowering the shear strength of soil until the failure of slope occurs. The ratio of the soil's actual shear strength to its reduced shear strength during failure is known as the resulting factor of safety. There are several advantages to this "shear strength reduction methodology" over slope stability analysis using the method of slices. The most significant benefit is the automatic discovery of the critical failure surface and the analysis of failure mechanisms involving deforming soil wedges.

Kourdey et. al. (2001) evaluated the slope stability by numerical methods and demonstrated how to combine a finite difference code-based numerical method with the limit equilibrium method of circular failure analysis. A software based on the limit equilibrium approach calculates the state of stress using a finite difference code before using it to calculate the safety factor. They used a finite difference code with this new methodology (Itasca-FLAC2D). A metric known as the global safety factor for this purpose was employed. It is concluded that it is appropriate to carry out limit equilibrium analysis utilizing a numerical method through FLAC2D for more challenging issues as it has more benefits of slope stability analysis.

Lata and Garaga (2010) presented the seismic slope stability analysis of the right abutment of a proposed railway bridge in the Himalayas, India, that would span a river and connect two enormous hillocks at a height of around 350 metres. They studied the heavily jointed rock mass that made up the rock slopes having variable joint spacing and orientations in different places. Given that the location was falling under seismic zone V according to India's earth quake zonation maps, seismic slope stability study of the slope under consideration was performed utilizing both pseudostatic and time response approaches. With the FLAC tool, the slope's stability was examined statistically. The findings of the temporal response study of the slope were shown as horizontal and vertical displacements along the slope, while the results of the pseudo-static analysis were shown in the form of FoS.

Cala and Flasiak (2010) examined the slope stability analysis with FLAC and limit equilibrium methods (LEM). Two-dimensional LEM have typically been used to assess the FoS for slopes. However, a slope's FoS can also be calculated using FLAC by gradually lowering the soil shear strength until the slope fails. The Shear Strength Reduction (SSR) Approach is the name of this technique. The benefits of SSR over limit equilibrium approaches have been cited by numerous publications. But often, they used very tiny models with straightforward geometry to test the effectiveness of SSR. In this work, comparisons with other limit analysis solutions were used to examine the SSR's accuracy. The FS calculated by SSR and the FoS discovered by Fellenius, Bishop, Morgenstern-Price, and Janbu were compared. It must be remembered that FS depends on the mechanical characteristics of the rock or soil. The main determinant of a trustworthy FoS analysis is the input data. It was concluded that the FS computed with SSR and FoS acquired via LEM are typically the same for a straightforward, homogenous slope. FS estimated with SSR is nearly identical to FoS from LEM for a small-scale slope with basic geometry and six units.

Slope design must take uncertainty into consideration because even a degree rise in cut slope can make a slope very unstable. Because traditional slope practice frequently relies on a factor of safety that cannot clearly address uncertainty, probabilistic slope stability analysis was created as a solution. Kainthola et al. (2013) reviewed the analysis of the stability of slope presented through a case study from the Deccan traps in Mahabaleshwar, India, via the finite difference code FLAC SLOPE 5.0. The analysis came to the conclusion that the slope is secure and has a safety factor of 4.75. The critical failure envelope was researched, and the plot of the shear strain of the slope provided by FLAC SLOPE was consistent with the findings. The growth of the 9.5-meter-long tension crack was another important finding.

Ureel and Momayez (2014) investigated and presented a review of the techniques utilized in actual modelling of huge rocks. The goal of the effort was to develop a resource for geotechnical engineers that includes information on the then current results, frequently used programmes, limitations of methods, and suggestions to further study and use modelling programmes. Included were three different techniques: (1) the distinct element method (discontinuum) using Itasca's Universal Discrete Element Code, UDEC; (2) the finite difference method (continuum) using Itasca's Fast LaGrangian Analysis of Continua, FLAC; and (3) the limit equilibrium technique using Geostudios: SlopeW. They concluded that LEM offers an efficient method for estimating the critical slip surface for slopes in static equilibrium and calculating the rock slope factor of safety. However, depending on the degree of heterogeneity of the rock slope, either the discontinuum or continuum model should be adequate; with FLAC being preferrable to UDEC when the rock slope has complicated large scale geology where there is feasibility of significant conditions of strain..

Singh et al. (2017) carried out a hill slope stability analysis using 2D and 3D analysis. They conducted an investigation along a portion of the NH-109 route using the most often used and acceptable criterion for analyzing the condition of slopes known as the factor of safety (FS). The rock mass strength for various litho-units exposed along the Rudraprayag-Agastmuni Road segment (NH-109), Rudraprayag district, Uttarakhand, were analyzed. In this study, fast Langrangian analysis of continuum (FLAC) codes were used to compare 2D and 3D numerical analysis based on the FDM. According to the study, the selected slope conditions did not significantly differ between the FS values derived from 2D and 3D analyses. For situations with uniform rock mass that were analyzed, the insignificant differences varied from 0.02 to 0.07. The study also demonstrated several significant analytical findings and the influences of variables on the final FS.

3. Slope Stability Analysis using FLAC/Slope 2D

The aim of the research is to model and analyze a weathered rock slope with complex geometry having benches using a numerical modelling software called FLAC/Slope 2D. The analysis includes the parametric assessment as follows:

- Pseudo-static analysis,
- Analysis of the stability in the presence of water table,
- Geogrids inclusion along the slope as a mitigation measure.

FLAC/Slope is a mini version of FLAC which is intended specifically to calculate the FoS values for slope stability analysis. FLAC's graphical user interface (GUI) operates the FLAC/Slope which helps in rapidly creating the models or solutions for soil or rock slopes. FLAC/Slope can be used as an alternative to the traditional LEM programs. LEMs usually makes a lot of assumptions like the location and angle of interslice forces. However, FLAC/Slope gives the complete solution of the stress or displacement, constitutive equations and equilibrium. With the aid of a set of properties, the modelled slope is eventually determined to be stable or unstable. By automatic performance of a series of simulations, and simultaneously altering the strength properties (strength reduction technique), the FoS can be calculated to determine the stability of a slope along with the identification of the location of the critical failure (slip) surface.

3.1 Rock Slope Parameters/ Properties

The rock slope boundary with the rock mass parameters or properties have been involved in the analysis during the numerical modelling for the 2D slope analysis and are presented in the following figures **Fig - 1**, **Error! Reference source not found.** and **Fig - 2**. The geometry of the slope is a modified example of Wyllie and Mah (2004) which is based on the example from Hoek and Bray (1981).

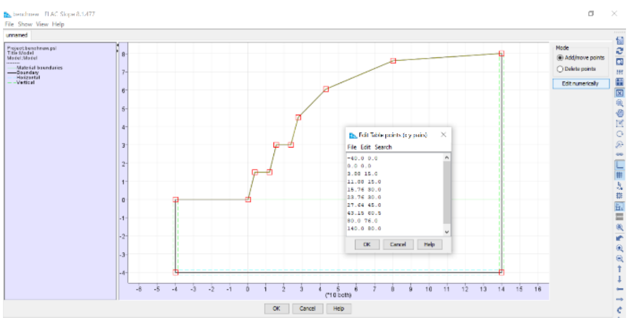

Fig - 1: Slope Boundary

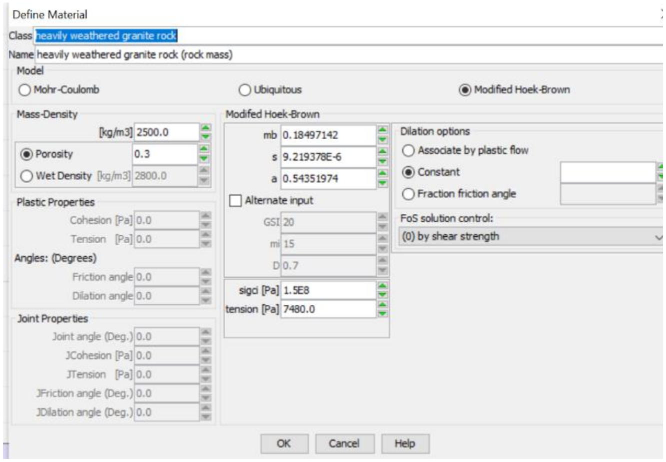

Fig - 2: Rock Slope materials' properties (Modified Mohr-Coulomb)

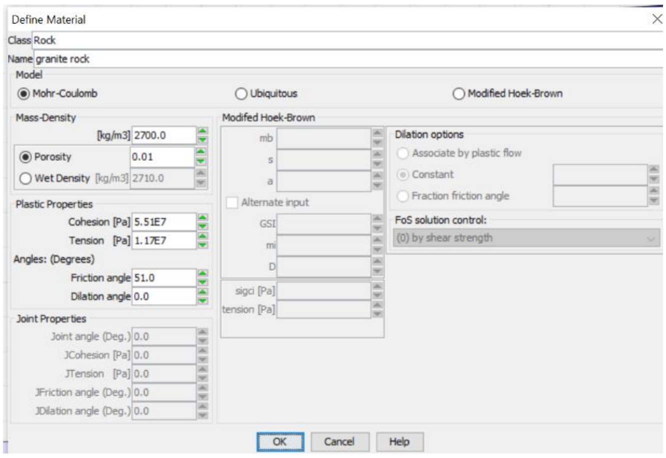

Fig - 3: Rock Slope materials' properties (Mohr-Coulomb)

3.2 Shear Strength Reduction (SSR) Technique

Gradual lowering of the slope's shear strength, the SSR technique is used for the FoS calculations in order to get the slope to a state of limiting equilibrium. The frequently used method for this approach is the Mohr-Coulomb failure criterion (e.g., applications by Zienkiewicz et al. 1975, Naylor 1982, Donald and Giam 1988, Matsui and San 1992, Ugai 1989, Ugai and Leshchinsky 1995).

In this method, the FoS or the safety factor (F) is defined according to the equations:

$$c^{trial} = \frac{1}{F^{trial}} c \qquad \textbf{(Equ. 1)}$$

$$\varphi^{trial} = arctan\left(\frac{1}{F^{trial}} \, tan\varphi\right) \qquad \textbf{(Equ. 2)}$$

A sequence of simulations is made by using the trial values of the factor (F^{trial}) in order to reduce the cohesion (c) and the friction angle (φ) until the slope fails or the failure occurs. "c" and "φ" values are increased till the limiting condition is achieved where the slope becomes stable. One such technique to determine the values of the slope strength which corresponds to the initiation of slope failure is to monotonically reduce or increase the strengths in smaller quantity till the state of failure is achieved. Consecutively, the bracketing method similar to the one suggested by Dawson, Roth, and Drescher (1999) is employed in FLAC/Slope.

3.3 Experimental Analysis using FLAC/Slope 2D

FLAC/Slope is explicitly designed to execute multiple analyses and parametric studies for projects related to stability of slopes. The program structure allows diverse models in a project to be straightforwardly created, stored and accessed for direct assessment of model results.

A FLAC/Slope analysis project is divided into 4 phases of Models, Build, Plot and Solve. The toolbars for each stage are shown in **Fig - *4*** below.

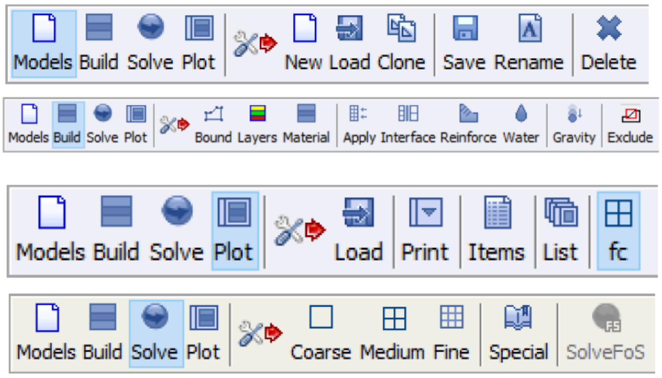

Fig - 4: Slope Analysis Stages (**models, build, solve, plot**)

Total of 5 different loading conditions were modelled in FLAC/Slope 2D to analyzed the stability of the weathered rock slope. The respective scenario for rock slope has been presented from ***Fig - 5*** to **Fig - *9***.

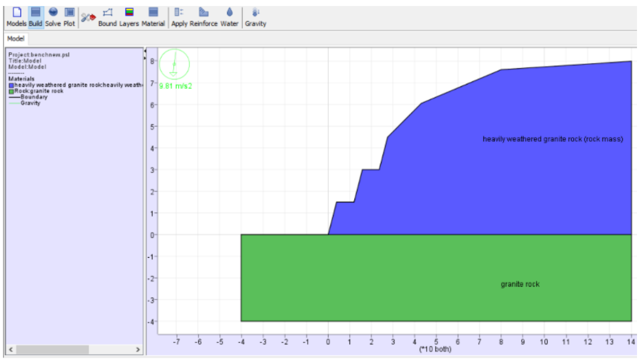

Fig - 5: Model 1, indicating the type of rock slope materials

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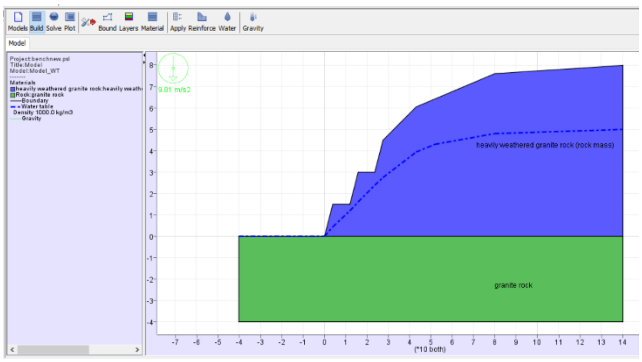

Fig - 6: Model 2, rock slope with the presence of water table

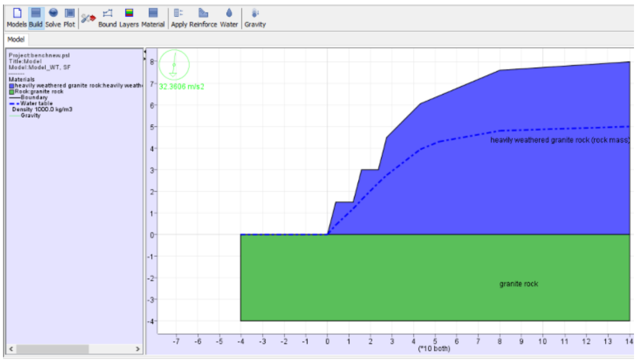

Fig - 7: Model 3, rock slope with water table and pseudostatic force

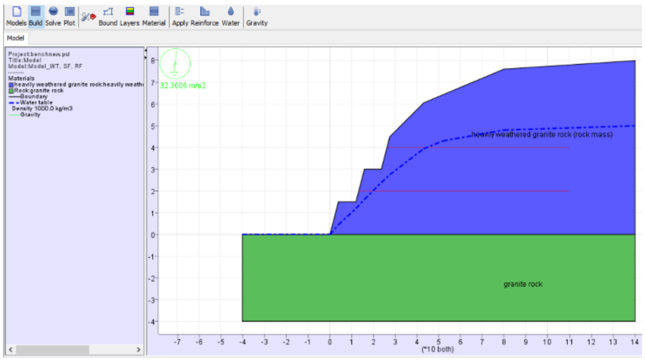

Fig - 8: Model 4, rock slope with water table, pseudostatic force and reinforcements

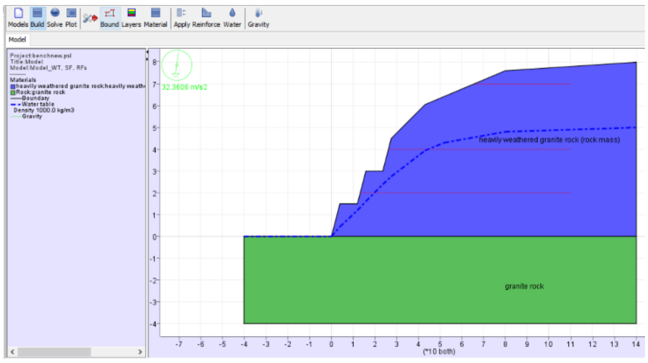

Fig - 9: Model 5, rock slope with water table, pseudostatic force and reinforcements

After building the models for different loading conditions, the FoS was each case was calculated to determine the stability of a slope along with the identification of the location of the critical failure (slip) surface. The FoS for all the cases are presented from **Fig -** ***10*** to **Fig -** ***14***.

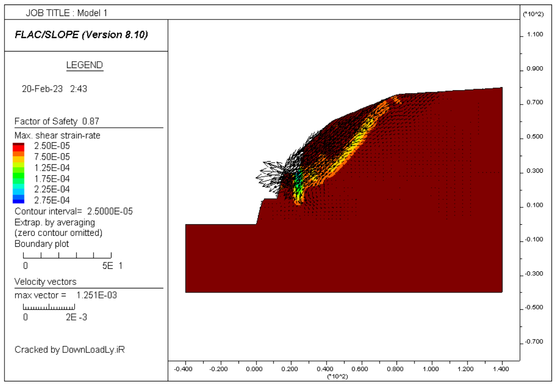

Fig - 10: Model 1 without water table or pseudostatic force

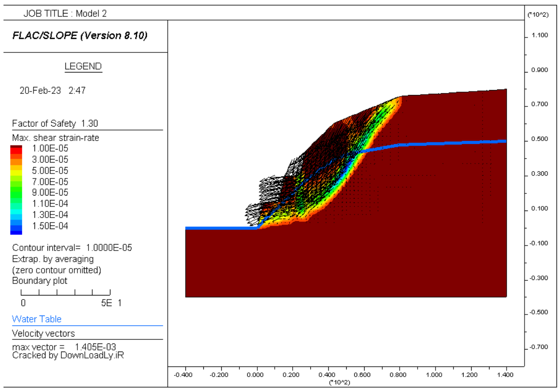

Fig - 11: Model 2 with water table and no pseudostatic force

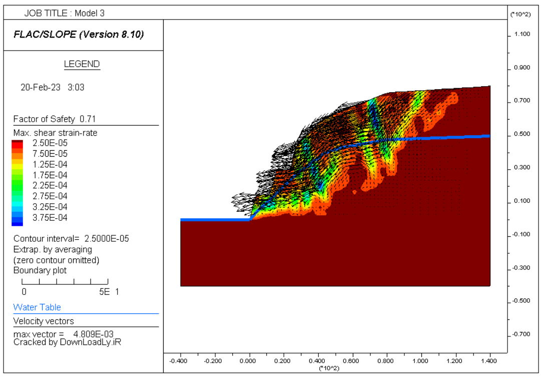

Fig - 12: Model 3 with both water table and pseudostatic force

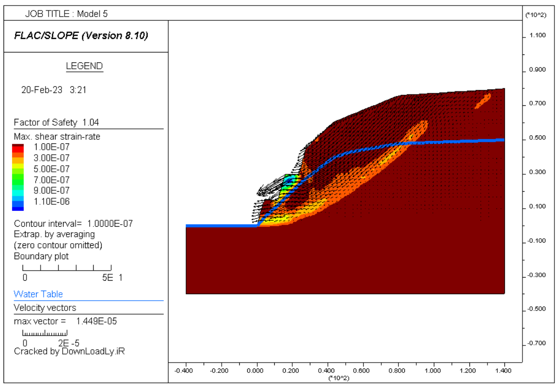

Fig - 13: Model 5 both water table, pseudostatic force and geogrids

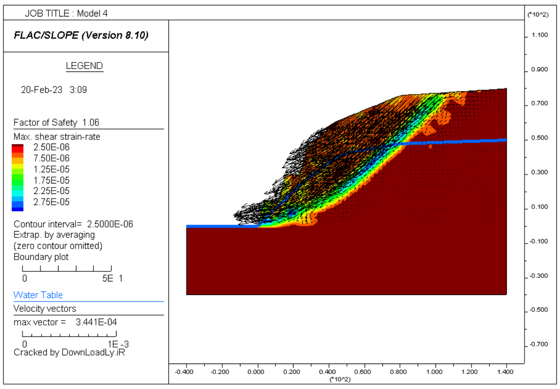

Fig - 14: Model 4 both water table, pseudostatic force and geogrids

4. CONCLUSIONS

Numerical modelling of slopes and the stability analysis through FLAC/Slope 2D is an excellent alternative to the traditional LEMs. It has numerous advantages over the LEMs. Firstly, any type of mode of failure naturally develops as it doesn't require to mention the trial surfaces' range beforehand. Secondly, there is no need to add artificial parameters like functions for interslice force angles unlike in LEMs. Thirdly, FLAC/Slope 2D has the ability to let multiple failure surfaces evolve if situation arises as such. Finally, integration of reinforcing elements has been realistically coupled in the models. Moreover, the solutions via numerical modelling ensures inclusion of both forces and kinematics, unlike the LEMs.

The results in **Table *1*** shows the material properties of the rock slope used for the modelling and analysis. **Table *2*** indicates the properties of geogrid reinforcements introduced to stabilize the rock slope which is subjected forces like the seismic force and the presence of water pressure. Finally, **Table *3*** displays the FoS values of different models for different material types. It can be concluded that the rock slope with complex geometry subjected to pseudostatic force in wet condition has the factor of safety of 0.71 which is unsafe. However, with the introduction of geogrids/ reinforcements along the slope as mitigative measure, the stability of the given rock slope increases by 45.5% to 49.3%.

Table 1: Material Properties

Material Properties - Mohr-Coulomb

Class Name	Density ρ	Cohesion c	Tension σ^t	Friction φ	Dilation ψ
Units	kg/m^3	Pa	Pa	Deg.	Deg.
Rock granite rock	2700.0	5.51E7	1.17E7	51.0	0.0

Material Properties - modifed Hoek-Brown

Class Name	Density ρ	m_b	s	a	σ_c	Tension σ_t
Units	kg/m^3	Pa	Pa	Deg.	Pa	Pa
heavily weathered granite rock heavily weathered granite rock (rock mass)	2500.0	0.18497142	9.219378E-6	0.54351974	1.5E8	7480.0

Table 2: Structural Element Properties

Structural Element Properties

Model	Property	Spacing m	Young's Mod. Pa	Tensile Str. N	Bond Str. N/m	Bond Fri. Deg.
Model_WT, SF, RFs	C1	Sheet	(Computed) 1.04000004E11	1.0E7	10000.0	30.0
Model_WT, SF, RFs	C2	Sheet	(Computed) 1.04000004E11	1.0E7	15000.0	30.0
Model_WT, SF, RF	C1	Sheet	(Computed) 1.04000004E11	1.0E7	10000.0	30.0
Model_WT, SF, RF	C2	Sheet	(Computed) 1.04000004E11	1.0E7	15000.0	30.0

Table 3: Factor of Safety Values for different models

Factor of Safety

Project	Model	Material Type	Shape	Mesh	Switches	FOS
benchnew	Model_1	Mohr-Coulomb, modified Hoek-Brown	General slope	Medium	hs	0.76
benchnew	Model_1_Medium	Mohr-Coulomb, modified Hoek-Brown	General slope	fc	hs	0.71
benchnew	Model_1_Medium_fc	Mohr-Coulomb, modified Hoek-Brown	General slope	hs	s	null
benchnew	Model_1_Medium_fct	Mohr-Coulomb, modified Hoek-Brown	General slope	hs	s	1.04
benchnew	Model_WT_SF_RFs_Medium_fct	Mohr-Coulomb, modified Hoek-Brown	General slope	hs	s	1.04
benchnew	Model_WT_SF_RF_Medium_fct	Mohr-Coulomb, modified Hoek-Brown	General slope	hs	s	1.06
benchnew	Model_WT_SF_Medium	Mohr-Coulomb, modified Hoek-Brown	General slope	fc	hs	0.71
benchnew	no_seismic_forces_Medium	Mohr-Coulomb, modified Hoek-Brown	General slope	fc	hs	1.30
benchnew	no_WT_Medium	Mohr-Coulomb, modified Hoek-Brown	General slope	fc	hs	0.87

The descriptor "fc" labels that the friction angle and cohesion have been included in the calculation procedure. The different descriptors used for the FoS parameters are detailed below:

f = friction angle

c = cohesion

t = tensile strength

uf = ubiquitous-joint friction angle

uc = ubiquitous-joint cohesion

ut = ubiquitous-joint tensile strength

hs = Hoek-Brown shear strength

hu = Hoek-Brown unconfined compressive strength

i = interface friction and cohesion

s = structural element grout strength

a = associated plastic flow rule

ACKNOWLEDGEMENT

The authors would like to thank all those who directly or indirectly contributed, supported and provided guidance towards the successful completion of the research work.

REFERENCES

1. Dawson, E. M., & Roth, W. H. (2020). Slope stability analysis with FLAC. In FLAC and numerical modeling in geomechanics (pp. 3-9). CRC Press.

2. Kourdey, A., AIheib, M., Piguet, J. P., & Korini, T. (2001). Evaluation of slope stability by numerical methods. S. arkk. a, Eloranta, editors. Rock mechanics—a challenge for society. Swetz and Zeitlinger Lisse, ISBN, 90(2651), 821.

3. Latha, G. M., & Garaga, A. (2010). Seismic stability analysis of a Himalayan rock slope. Rock Mechanics and Rock Engineering, 43, 831-843.

4. Cala, M., & Flisiak, J. (2020). Slope stability analysis with FLAC and limit equilibrium methods. In FLAC and numerical modeling in geomechanics (pp. 111-114). CRC Press.

5. Kainthola, A., Verma, D., Thareja, R., & Singh, T. N. (2013). A review on numerical slope stability analysis. International Journal of Science, Engineering and Technology Research (IJSETR), 2(6), 1315-1320.

6. Ureel, S., & Momayez, M. (2014). An investigation of the limit equilibrium method and numerical modeling for rock slope stability analysis. In Rock mechanics and its applications in civil, mining, and petroleum engineering (pp. 218-227).

7. Singh, R., Umrao, R. K., & Singh, T. N. (2017). Hill slope stability analysis using two- and three-dimension analysis: A comparative study. Journal of the Geological Society of India, 89, 295-302.