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# LANDSLIDES ANALYSIS FOR HIMALAYAN CONDITIONS

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## ABSTRACT

The main objective of this study is to carry out a landslide analysis associated with massive rock slope failure under Himalayan conditions and to determine the sensitivity to different triggering mechanisms. To represent Himalayan conditions, the Arniko Highway of Nepal is considered as a pilot project for this proposed study. The analysis tool Swedge 5 is used to evaluate the stability of the case. Swedge is a quick, interactive, and simple-to-use analysis tool for evaluating the stability of surface wedges in rock slopes. The sensitivity plot of joint attitudes shows that the dip direction of joints has a greater influence on the Factor of Safety compared to the absolute value of dip. The study also indicates that Joint Roughness Coefficient (JRC) has a significant influence on the Factor of Safety. The calculation results produced by the program Swedge indicate that the probability of failure of the slope is 53% for the combination of slope geometry, shear strength, and water pressure parameters assumed. This is a very high value.

**Keywords**: Himalayan Conditions, Landslide Analysis, Sensitivity Analysis, Probability Of Failure.

## I. INTRODUCTION

### BACKGROUND

Landslides resulting from massive rock slope failure are major hazards in the Himalayas (see Figure 1). These landslides are frequently multiphase events in which a disintegrating rock mass, involved in an initial rockslide and subsequent rock avalanches, transforms into a massive, rapid debris flow (Cassassa et al., 1993). Moreover, secondary processes associated with massive rock failure constitute an important component of the hazard. These processes include the formation and failure of landslide dams and the generation of landslide tsunamis. The nature of triggers for large landslides, however, is not well understood. The most likely triggers are seismic shaking and intense monsoon precipitation events. Water pressure is the main issue that will be addressed in this paper on the fundamentals of landslide hazard analysis under Himalayan conditions.

**Figure 1**: Massive rock slope failure along Prithvi Highway in Nepal

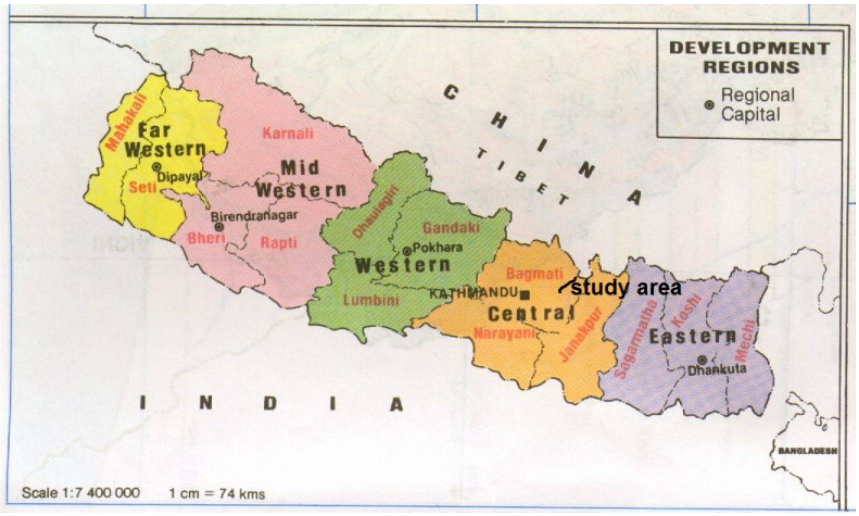

**Figure 2**: Location of study area

To represent the Himalayan conditions, the Arniko Highway in Nepal is considered a pilot project for this proposed study. Nepal, a mountainous country situated in the central part of the Himalayan arc, is tectonically sandwiched between Tibet to the North and India to the South (see Figure 2).

Geologically, the major part lies on the edge of the Indian plate, and the minor part of the northern region lies on the Euro-Asian plate. Globally, Nepal boasts the highest relative relief on Earth, with the lowest elevation at 70 m above sea level and the maximum elevation at the summit of Sagarmatha (Mount Everest) reaching 8848 m. In a country with such an extreme range of elevations, the climate varies greatly, ranging from subtropical on the lowland plains to glacial in the high mountains. Throughout most of the country, the climate is strongly monsoonal. The actual levels of rainfall during the monsoon period vary considerably from year to year, depending on a range of climatic factors generally associated with global and regional climate systems.

It is well-recognized that landslide occurrences are extreme in the Himalayas, particularly within Nepal. An area such as the Himalayas can be expected to have a high level of natural landslide activity. The annual occurrence of landslides heavily depends on the summer monsoon. Specifically, although the monsoon period represents 60-80% of the annual total precipitation and 55-80% of runoff (Shrestha et al., 2000), it accounts for 92% of landslide fatalities and 90% of fatal landslides.

## II. OBJECTIVES

The main objective of this study is to conduct a landslide analysis associated with massive rock slope failure under Himalayan conditions and to determine the slope sensitivity to different triggering mechanisms.

## III. DESCRIPTION OF THE CASE

**Figure 3**: Location map of Arniko Highway

The Arniko Highway (see Figure 3) is a heavily used motorway linking the Kathmandu Valley with Tibet. This project has been selected to serve as a pilot study area because the highway along the Bhotekoshi and Sunkoshi River is extremely prone to landslides. During the monsoon period the road is frequently blocked due to landslides, and causes hardships to human settlements in the area.

## DESCRIPTION OF SITE (GATI VILLAGE AREA)

**Figure 4**: Landslide at specific site (source Subedi, N., 2010)

A photo and cross-section of the specific site considered here are shown in Figures 4 and 5, respectively. The attitude of discontinuities and the slope face of this site are given in Table 1. Based on detailed field mapping, it can be observed that four discontinuity sets are predominant in the Gati Village area (see Table 1). The plane of the slope face ($\psi_f$) is, on average, 85°/225° (dip/dip direction). A stereographic projection plot (lower hemisphere) of these discontinuities is presented in Figure 6, which indicates that the site is conducive to wedge failure due to joint sets 1 and 2.

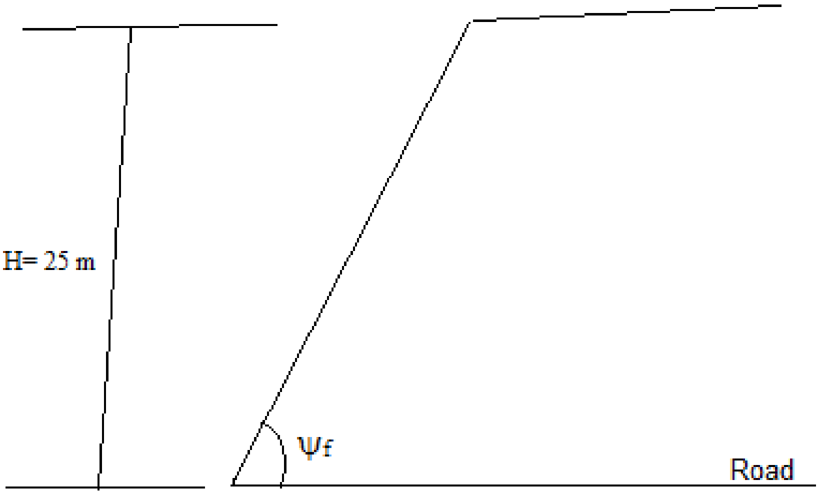

**Figure 5:** Cross section of specific site

**Table 1**: Attitude of Discontinuities and Slope Face (Source: Subedi, N. 2010)

| Joint Set number | Attitude (dip/dip direction) |
|---|---|
| Joint Set 1 (J1) | 68°/132° |
| Joint Set 2 (J2) | 76°/ 271° |
| Joint Set 3 (J3) | $72^0/190^0$ |
| Joint Set 4 (J4) | 49°/015° |
| Slope Face ($\psi_f$) | 85°/ 225° |
| Upper Slope Face (USF) | 12°/ 225° |

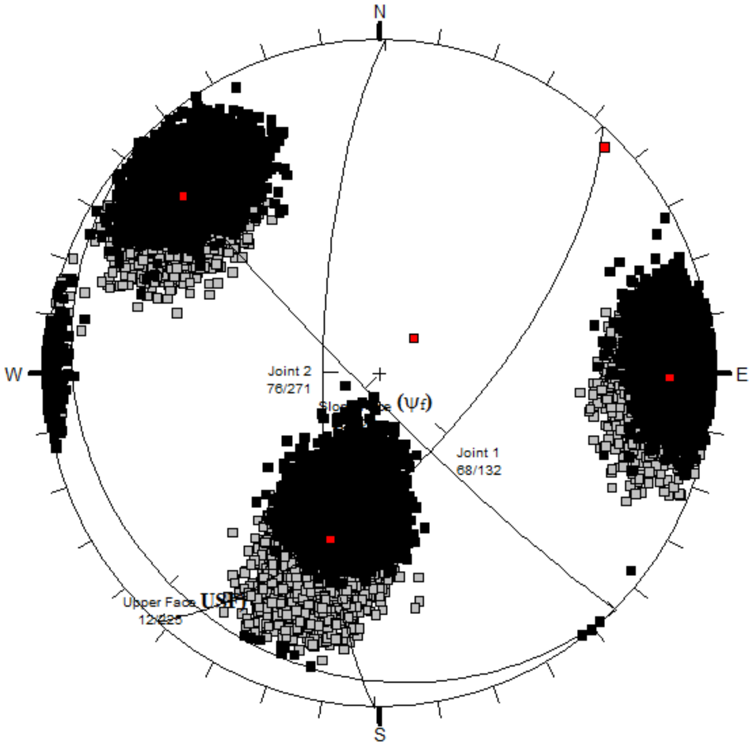

**Figure 6**: Stereographic projection of joint sets and slope face (Lower hemisphere)

## IV. ESTIMATION OF INPUT PARAMETERS

The main input data for analysis includes geometry, water pressure, and shear strength parameters.

**GEOMETRY:**

Rock slope stability is highly dependent on discontinuity characteristics, and the random properties of each parameter have an important effect on the analysis. Therefore, random properties for geometric and strength parameters of discontinuities play a critical role in the analysis. Discontinuity parameters include orientation, length, and spacing. Many rock slope failures seem to occur by sliding along major individual discontinuities, such as fault planes and bedding planes, or along combinations of these planes. In massive rock slopes, it is highly unlikely that a network of fully persistent natural discontinuities exists a priori to forming a complete 3-D surface enabling kinematic release (Eberhardt et al., 2004). Einstein et al. (1983) suggested that the persistence of key discontinuity sets is, in reality, more limited, and that a complex interaction between existing natural discontinuities and brittle fracture propagation through intact rock bridges is required to bring the slope to failure.

**GROUNDWATER PRESSURE:**

A heavy precipitation event, such as an intensified monsoon, can trigger a large landslide in two ways: (a) destabilization of slopes through increased cleft-water pressure, and (b) flooding that rapidly removes a significant amount of sediments and undercuts and destabilizes slopes. Many large landslides occur or reactivate during or after heavy rainfall during monsoon periods. There is a strong relation between the total annual precipitation and the frequency of landslides in Nepal. The number and scale of landslides increase with precipitation. The number of large landslides increases abruptly at > 250 mm in two days with an average intensity of > 80 mm/hour in one day (Li, 1990). For the estimation of water pressure along sliding planes, a triangular distribution of water pressure, which represents a model where water enters freely at the top but is fully drained at the toe after having reached a maximum hydrostatic pressure at a height corresponding to 50% of the slope height, can be used for Himalayan conditions (see Fig. 7). The idealized triangular distribution will seldom match perfectly with the real situation during heavy rainfall, and it often exaggerates the resultant pressure because joints and cracks will often provide certain drainage towards the slope face. But due to the shortcomings of alternatives, the idealized triangular distribution model is common today (Nilsen and Palmstrom, 2000).

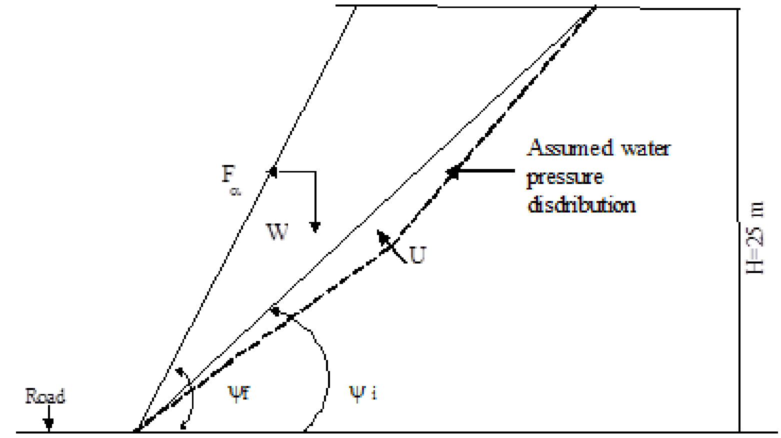

**Figure 7:** Geometry of wedge and assumed water pressure along sliding plane

In Figure 7,

$H$ = Slope height = 25 m

$\psi_f$ = Slope angle = 85 deg.

$\psi_i$ = Plunge of line of intersection of two planes

W = Weight of potentially sliding plane

U = Water pressure resultant

$F\alpha$ = Seismic load = 0

**SHEAR STRENGTH PARAMETERS:**

The natural discontinuity surface in rock is never smooth. The undulation on a natural joint surface has a significant influence on its shear behavior. Generally, this surface roughness increases the shear strength of the surface, and this strength increase is extremely important in terms of the stability of rock slope. In order to obtain shear strength values for use in rock slope design, field investigation and testing is required. This may take the form of very sophisticated laboratory tests or in-situ tests. The choice of the most appropriate method depends upon the nature of the problem being investigated, the facilities that are available and the amount of time and money, which have been allocated to the solution of the problems. In principle, there are four main alternatives: Empirical methods, Laboratory shear testing, Field shear testing and Back Analysis for finding friction parameters. Empirical methods proposed by Barton and Choubey (1977) are often used today. Barton and his co-workers (1973, 1976, 1977, and 1990) studied the behavior of natural rock joints and have proposed the following empirical Equation for predicting the shear strength of rough joints:

$$\tau = \sigma_n * \tan(\phi_b + JRC \log_{10}(\sigma_j/\sigma_n)) \quad \text{(i)}$$

Where,

$\tau$ = Shear strength

$\phi_b$ = Basic friction angle

$\sigma_n$ = Defined normal stress on the potential sliding plane

JRC = Joint roughness coefficient

$\sigma_j$ = Joint compressive strength of the rock material adjacent to the discontinuity

**Table 2**: Field and Laboratory data: (Source: Subedi, N. 2010)

| Rock type | Schist |
|---|---|
| Texture | Medium to Coarse |
| Color | Grey |
| Thickness of beds | 5-40 cm |

| | |
|---|---|
| Weathering grade | Moderately weathered |
| Infilling material | Clay |
| Rock Quality Designation (RQD) | 56 % |
| Unit weight of rock | 25 KN/m$^3$ |
| Joint wall compressive strength (JCS) | 28 MPa |
| Basic friction angle | 30 degrees |
| Joint roughness coefficient (JRC) | 7 |

To use empirical methods, one has to estimate the joint compressive strength, joint roughness coefficient and basic friction angle. Methods are well developed today to quantify these parameters. For the present case study, the Barton- Bandis method is used to estimate the shear strength parameters. The field and laboratory data for the specific site are given in Table 2.

## V. METHODS OF ANALYSIS

In order to analyze and evaluate the potential hazard relating to an unstable rock slope, it is essential to understand the process and mechanism driving the instability. Today, a vast range of slope stability analysis tools exist for rock slopes: these range from simple limit equilibrium techniques to sophisticated numerical modeling. It has become necessary for the practitioner to understand the varying strength and limitation inherent in each of the different methodologies. Here Slide 6.0 (ref. rocscience.com) is used since it is one of the most comprehensive slope stability analysis software available, complete with finite element groundwater seepage analysis, rapid drawdown, sensitivity and probabilistic analysis and support design. Slide 6.0 is the only slope stability software with built-in finite element groundwater seepage analysis for steady state or transient conditions. Flows, pressures and gradients are calculated based on user defined hydraulic boundary conditions. Slide 6.0 also has extensive probabilistic analysis capabilities – one can assign statistical distributions to almost any input parameter, including material properties, support properties, loads, and water table location. The probability of failure/reliability index is calculated, and provides a reasonably objective measure of the hazard associated with a particular slope design. Sensitivity analyses allow one to determine the effect of individual variables.

## VI. ANALYSIS RESULT AND ITS INTERPRETATION

The analysis tool Swedge 5 (component of Slide 6) is used for evaluating the stability of the case. Swedge is a quick, interactive and simple to use analysis tool for evaluating the stability of wedges in rock slopes, defined by two intersecting discontinuity planes, the slope surface and an optional tension crack. For the particular site deterministic and probabilistic analyses are carried out. Input parameters and analysis results are presented in Table 3.

In the deterministic analysis, Swedge computes the Factor of Safety (FS) for a particular wedge. In the probabilistic analysis, statistical distributions of the input parameters (e.g., joint orientation, shear strength, water level) are used. This results in a safety factor distribution from which a probability of failure (PF) is calculated. The effect of uncertainty or variability in the input parameters can be explored using a Sensitivity Analysis. Initially selected model parameters are varied across a range of values, and the effect on the safety factor is calculated. This can be illustrated in sensitivity plots, as shown in Figures 9 and 10. Specifically, the gradient of a curve for a parameter indicates the effect that the parameter has on the factor of safety (steeper curve, greater effect). The stereographic projection (lower hemisphere) for the site was presented in Fig. 6 and shows that the site is conducive to wedge failure (also see Table 3). A 3D view of the mean wedge is shown in Fig. 8 (also refer to Tab. 4).

**Table 3**: Input Parameters and Results

| Input Parameters | Random Variable | Deterministic Analysis | Probabilistic Analysis |
|---|---|---|---|
| Slope height (m) | - | 25 | 25 |
| Slope angle (deg) | - | 85 | 85 |
| Friction angle (deg) | yes | 30 | Lognormal distribution; Min 26., mean 30, max 34 |
| JRC | yes | 7.0 | Lognormal distribution; Min 5, mean 7, max 9 |
| JCS (t/m$^2$) | yes | 2800 | Lognormal distribution; Min 2400, mean 2800, max 3200 |
| Rock unit weight (t/m$^3$) | - | 2.5 | 2.5 |
| Water unit weight (t/m$^3$) | - | 1.0 | 1.0 |
| Tension crack | yes | - | - |
| Dip Joint 1 (deg) | - | 68 | 68 |
| Dip direction Joint 1 (deg) | yes | 132 | Fisher distribution; Min 122, mean132, max 142 |
| Dip Joint 2 (deg) | - | 76 | 76 |
| Dip direction Joint 2 (deg) | yes | 271 | Fisher distribution; Min 261, mean 271, max 281 |
| **Analysis Results** | | | |
| Failure mode: WEDGE | Sliding on intersection line Joints 1& 2, Plunge 47 deg., Trend 196 deg. | | |
| Safety factor | | 0.99 | 0.99 |
| Probability of failure | | | 0.53 |
| Wedge weight (t) | | 3820 | 3820 |
| Effective normal stress – Joint 1 (t/m$^2$) | | 5.28 | 5.28 |
| Effective normal stress – Joint 2 (t/m$^2$) | | 1.85 | **1.95** |
| Shear strength – Joint 1 (t/m$^2$) | | 6.09 | 6.09 |
| Shear strength – Joint 2 (t/m$^2$) | | 2.5 | 2.5 |
| Water pressure – Joint 1 (t) | | 1462 | 1462 |
| Water pressure – Joint 2 (t) | | 1939 | 1939 |

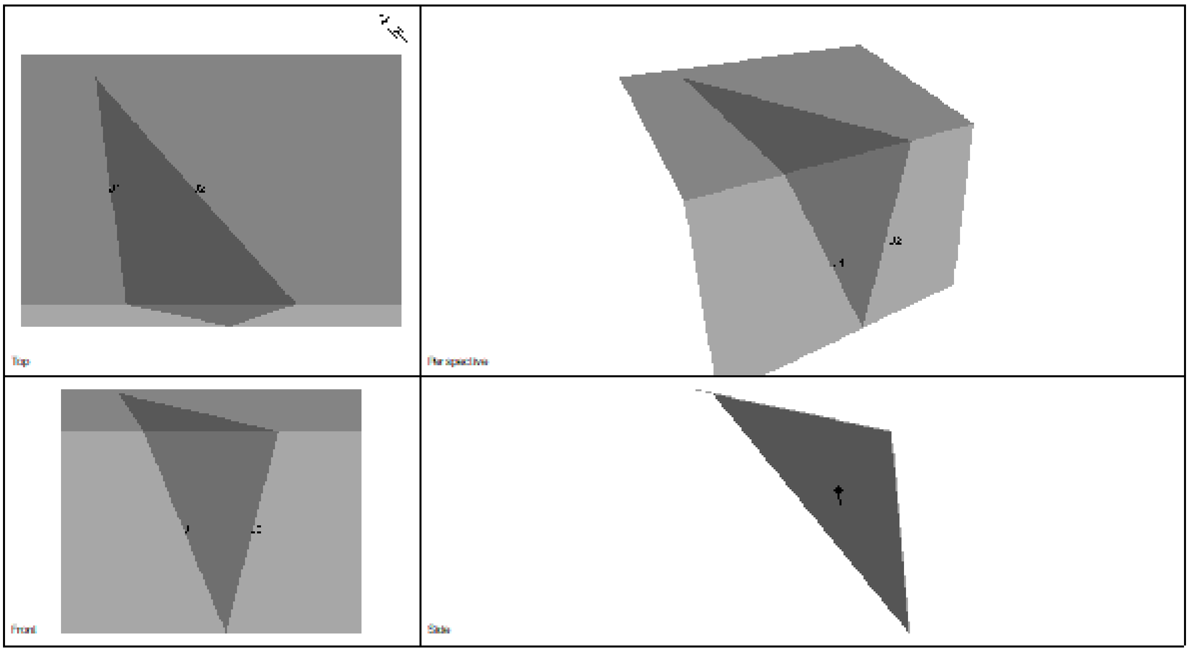

**Figure 8**: 3D View of wedge

**Table 4:** Wedge Vertics – Mean Wedge

| Point | X | Y | Z |
|---|---|---|---|
| 124 | 0.000 | 0.000 | 0.000 |
| 134 | -5.687 | 8.780 | 25.000 |
| 234 | 6.180 | -3.087 | 25.000 |
| 123 | 7.881 | 26.706 | 29.733 |

In Table:

- Coordinates in Easting, Northing, Up Format
- 1=Joint1, 2=Joint2, 3=Upper Face, 4=Slope

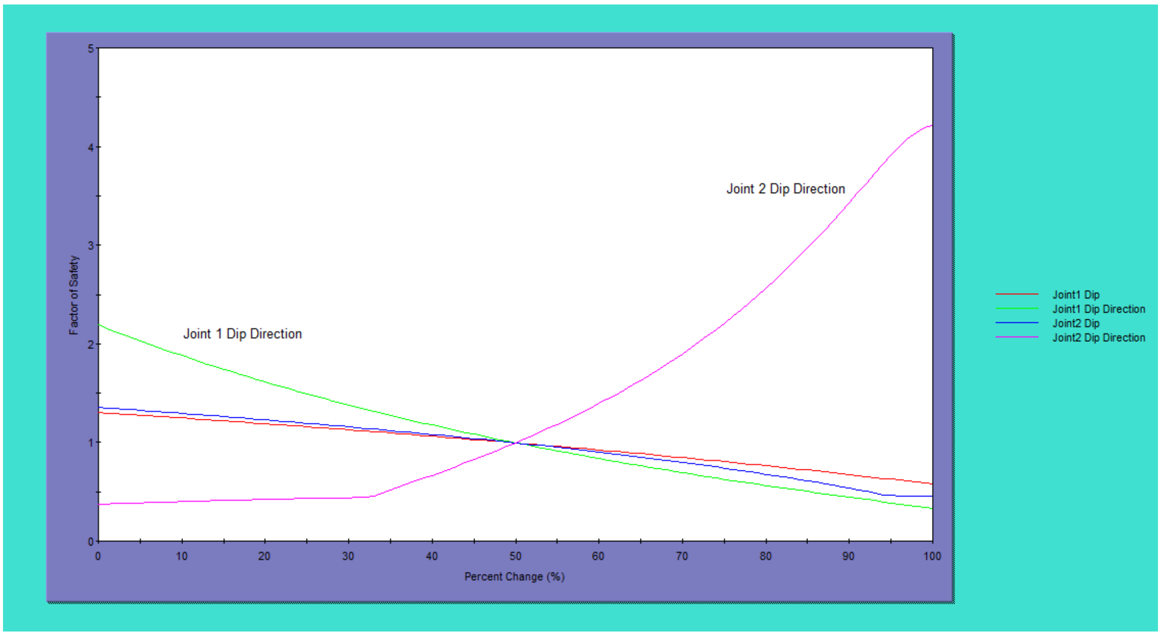

**Figure 9**: Sensitivity plot of the attitudes of joints 1 and 2

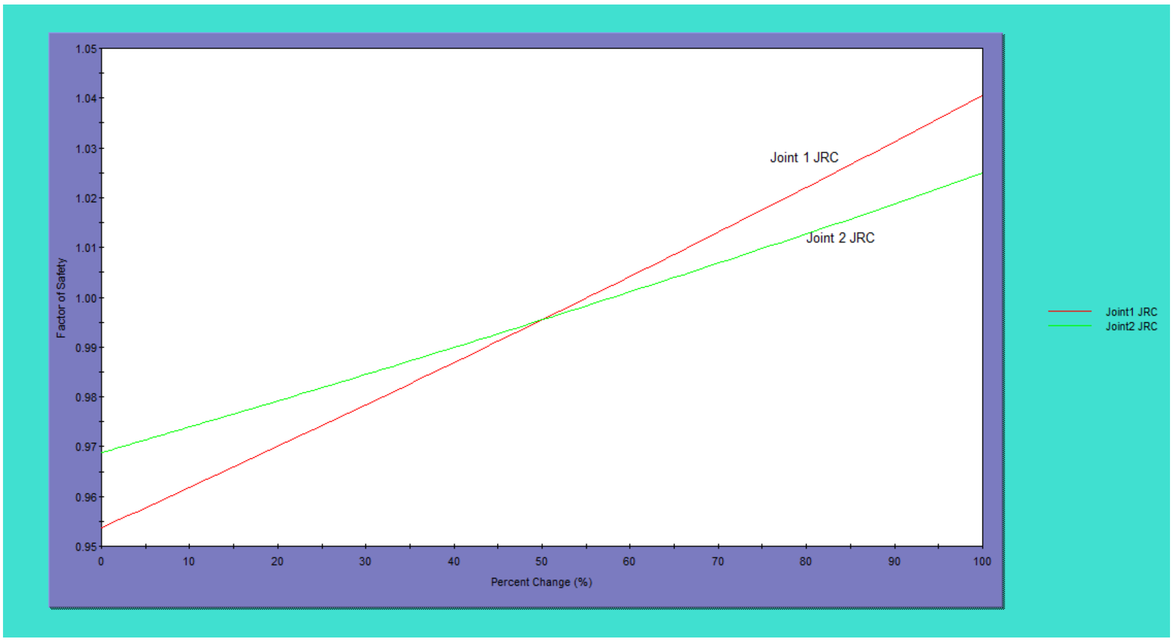

**Figure 10**: Sensitivity plot of JRC

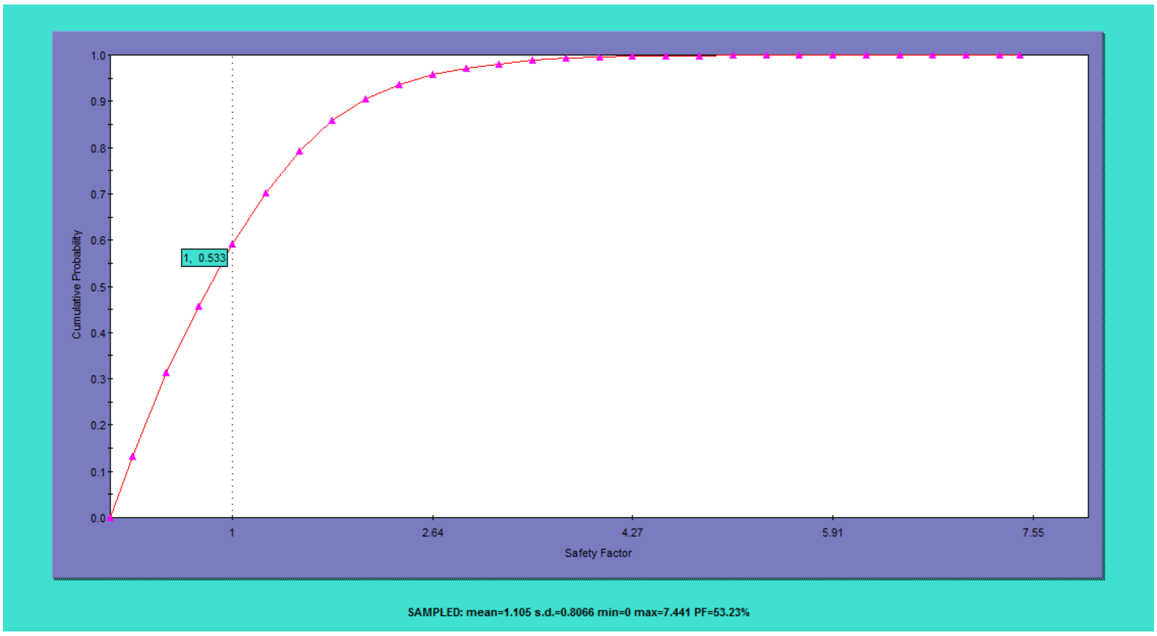

**Figure 11**: Plot of cumulative probability

The sensitivity plot of joint attitudes (ref. Fig. 9) shows that the dip direction of joint 2 (271 degrees) has a greater influence on the Factor of Safety compared to the dip direction of joint 1 (132 degrees) for this specific site. Figure 9 also indicates that the dip of both joints has very little effect on the Safety Factor. Figure 10 further illustrates that Joint Roughness Coefficient (JRC) has a significant influence on the Factor of Safety.

The plot of Cumulative Probability of Failure for the site is shown in Figure 11. The calculation results produced by the program Swedge indicate that the probability of failure for the slope is 53%, which is considered very high. This result is based on the assumed combination of slope geometry, shear strength, and water pressure parameters.

## VII. CONCLUSION

The analysis tool Swedge 5 is utilized to evaluate the stability of slopes under Himalayan conditions at a specific site. Both deterministic and probabilistic analyses are conducted for this particular location. In the deterministic analysis, the Factor of Safety (FS) for a specific wedge is computed. In contrast, the probabilistic analysis aims to quantify and model the variability and uncertainty of input parameters, such as joint orientation, shear strength, and water level. As demonstrated in this paper, the dip direction of joints exerts a greater influence on the Factor of Safety compared to the absolute value of the dip. The study also highlights the significant impact of Joint Roughness Coefficient (JRC) on the Factor of Safety. The calculated results suggest a 53% probability of failure for the slope, considering the assumed combination of slope geometry, shear strength, and water pressure parameters. This percentage indicates a notably high risk of failure.

## ACKNOWLEDGEMENT

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