

Probabilistic and Sensitivity Investigation for the Hill Slopes in Uttarakhand, Lesser Himalaya, India

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Abstract Himalayas is one of most seismically active mountain chain in the world. Landsides and the mass wasting are a prevalent phenomenon in this region. There are a considerable number of human populations living in the hilly regions which are under a constant threat of hill slope collapse. The stability assessment of these hills is one of the vital steps to mitigate the danger to this natural calamity. The deterministic factor of safety calculations have been traditionally used for the hazard evaluation of the hill slopes. For the present study, two hill slopes, Chandaak and Chhera, have been selected for probabilistic and sensitivity analysis. These areas were analyzed using limit equilibrium method for calculation of factor of safety and probability of failure. The factors of safety were calculated using Bishop's method of slice. The analysis was done for both dry and saturated conditions. At the same time the sensitivity of each parameter on the factor of safety was analyzed. The probability analysis of these areas was done using Monte-Carlo simulation which uses randomly selected discrete values of each variable from their probability distribution. In both the hill slopes the rock mass has varied weathering grade, ranging from highly weathered to moderately weathered. Seasonal variation in the rock mass strength was accounted for in the study. Chhera hill were quantified to have high FOS in both cases (dry and saturated) as compared to the Chahdaak hill, making them more vulnerable.

Keywords: Himalayan, Rock Mechanics, slope stability, numerical simulation, sensitivity analysis

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1. Introduction

Himalayas are a seismically active young mountain belt. The occurrence of landsides and other types of mass wasting are quite a widespread phenomenon in this region. A large number of populations living in the hilly region are under the constant threat of the landslides. The swift growth in population and the small scale mining activities further up the risk to the life of people in these areas. The stability assessment of these hills is one of the steps to mitigate the danger to this natural calamity. The deterministic factor of safety calculations have been traditionally used for the threat evaluation of the hill slopes. The chief demerit of these calculations is that they use a single value for the whole rock mass other than the fact that the rock mass by nature are inherently heterogeneous and can have different physico-mechanical properties in a span of few meters (Singh et al., [1]; Sarkar et al., [2]; and Verma et al., [3]). It is now widely accepted that deterministic methods for analyzing slope stability do not allow for the uncertainty and variability of the strength parameters of soil and rock masses, often noted in the literature, slope failures may occur even though the calculated factor of safety is greater than unity (Verma et

al., [4]; Kainthola et al., [5,6]). The variation and uncertainty in the geotechnical data for slope stability appraisal may occur as scattered values for discontinuity orientations and geometries such as discontinuity trace length and spacing, and in laboratory or in situ test results (Park et al., [7]). Previously, work has been done to overcome bound this uncertainty (Baecher [8]; Einstein and Baecher [9]).

The probabilistic analysis is one of the techniques which are being employed to overcome the uncertainties in the stability assessments of both rock and soil slopes. The probabilistic analysis considers the ambiguity in geotechnical parameters and results (Kainthola et al., [5,6,10,11]). In the probabilistic method, the analysis carries out the analysis of random properties of the rock mass. Random properties of input parameters used for probabilistic analysis and are obtained by statistical evaluation of available geological and geotechnical data. Subsequently, using random properties of input parameters determined previously, probability of failure is evaluated (Park et al., [1,7]). Limited or uncertain data can be utilized in analysis and judgments can be quantified (Whittlestone et al., [12]). Probabilistic risk analysis is used in an effort to overcome the subjective judgment of slope stability parameters and resultant, single value, factor of safety. The subjectivity and uncertainties are due

to the spatial variability of the material properties and their measurements, as well as uncertainties in reliability of the hypothesis carried out to approximate the mechanical behavior of the geo-material. Monte Carlo simulation is used to generate random numbers from which each of the variable values is assigned. It is required that the distribution of all the input variables is either known or assumed. The factor of safety can be assessed to determine the probability of failure. The hill slopes were also analyzed for sensitivity for each of the input parameters to see the change of which geo-mechanical factor has the most influence in the factor of safety of the hill slopes. The analyses were done using Limit equilibrium method. In limit analysis, the objective is generally to determine the collapse load; whereas the factor of safety is calculated in method of slices. The methods of slices are based on the limit equilibrium theory. Various methods of slices were proposed in the 1950s and 1960s. These methods were proposed with different assumptions on the shape of slip surfaces and the interslice forces. The most commonly used methods of slices comprised the Fellenius method, the methods of Bishop [13], Janbu [14], Morgenstern & Price [15] and Spencer [16]. Other efforts (Chen & Morgenstern [17]; Chen & Shao [18]; Chen [19]) were made in the 1980s to develop efficient and accurate optimizing techniques for the solution of the critical slip surface and the minimum factor of safety.

In the present investigation two 500m high hill slopes, Chandaak and Chhera in Pithoragarh, lesser Himalaya, India where small scale mining of magnesite is also taking place, were analyzed for the probability of failure through probabilistic and sensitivity analysis using limit equilibrium method. The Chandaak hill slope is composed of magnesite veins containing dolostone while the Chhera hill slope is predominantly made up of phyllites. In both the hill slopes the rock mass has varied weathering grade, ranging from highly weathered to moderately weathered. The two hills slopes were chosen due to their proximity to human settlements and mining activities. Previously, during the rainy season, some minor slope failure

activities had taken place in the area which were reported in the local media. The analysis was carried out for both dry and saturated condition accounting for the seasonal variation in the rock mass strength.

2. Geology of the Area

The present investigation was undertaken to study the instability of hill slopes in and around Pithoragarh District, Uttarkhand, India in the lesser Himalaya. The area around Pithoragarh exposes the rocks of Gangolihat formation and the Berinag quartzite. The rocks exhibit a variation in its strike from NNE-SSW to NE-SW direction with low to moderate amount of dip mainly towards northern direction. The Pithoragarh Formation present in the study area consist of five members namely – the Thalkedar Limestone, Sor Slate, Unnamed member, Gangolihat Dolomite and lastely the Karlani Slates in the Pithoragarh-Bageshwar area while in the Tejam-Kapkot area the five members are Tejam Dolomite, Dewalchaura Slate, Balgad Dolomite, Kapkot Dolomite and finally Saline Slate. The Pithoragarh / Tejam Formation of Upper Precambrian to Lower Palaeozoic age represent a calcareous facies. The uppermost Berinag Formation in the area consists of a single member, Berinag Quartzite representing an arenaceous facies of Devonian to Lower Carboniferous age (Valdiya [20]).

2.1. Field Investigation

The hill slopes of Chandaak and Chhera were visited for collection for field data and sampling (Figure A&B). The hill slopes were investigated for average slope angle, slope height 502m & 32° for Chandaak area and 500m & 38° for Chhera area. The discontinuity orientation, persistence, and spacing in the rock mass were also measured which were used in the estimation of the Geological strength Index (GSI) of the hill slopes (Hoek et al. [21]). 10 to 20 GSI readings were taken for each hill slope.



Figure 1. A) Debris flow near Chandaak area, B) A planar rock failure near Chhera area

The representative rock blocks collected from different vulnerable locations were brought and specimens of different geometrical shapes were prepared for performing the different test to evaluate instability. The tests were carried out as per International Society of Rock Mechanics (ISRM) suggesting methods (ISRM, [22]). The 10

samples were tested for their uniaxial compressive strength and unit weight. The laboratory tests were conducted for both dry and saturated conditions. The samples were kept under water for 72 hours to measure the reduction in their strength after the saturation.

2.2. Random Variables

As input parameters for the model, uniaxial compressive strength (UCS), GSI and unit weight of the rock mass don't have a single value but are rather scattered, they were used as random variable for the probability and sensitivity analysis (Table 1). The normal probability distribution function was used for the variables. The normal PDF was used as the maximum number of data was within three times the standard deviation. The analysis was done using Limit equilibrium method using

GSI, intact rock constant (m_i), UCS, disturbance factor (D) (Hoek [21]). As small scale mining is taking place in the area, a disturbance factor of 0.7 was taken for both the areas studied. The intact rock constant (m_i) value of 9 for Dolostone and 7 for Phyllite was used for the analysis as suggested by (Hoek [21]). The GSI readings were taken at the most critical sites and were averaged out. The mean, standard deviation, and relative maximum and minimum values were calculated for the scattered input parameters. The relative minimum and maximum values indicates the maximum and minimum distance from the mean value.

Table 1. Statistical distribution of the input parameters for the rock mass

Area	Lithology	Rock condition	Parameter	Mean	Standard Deviation	Relative Maximum Value	Relative Minimum Value	Probability Distribution Function
Chandaak	Dolostone	Dry	UCS Intact (MPa)	38.663	6.3	10	18.5	Normal
			Unit Weight (KPa)	27.1	1	1.5	2	Normal
			GSI	55	15	15	30	Normal
		Saturated	UCS Intact (MPa)	30.76	5.2	14.5	15	Normal
			Unit Weight (KPa)	27.58	1.1	2.1	1.2	Normal
			GSI	55	15	15	30	Normal
Chhera	Phyllite	Dry	UCS Intact (MPa)	54.65	7.1	11.3	16.2	Normal
			Unit Weight (KPa)	26.6	0.54	1.56	1.45	Normal
			GSI	60	10	20	35	Normal
		Saturated	UCS Intact (MPa)	43.7	5	10	15	Normal
			Unit Weight (KPa)	27.58	1	1.5	2	Normal
			GSI	60	10	20	35	Normal

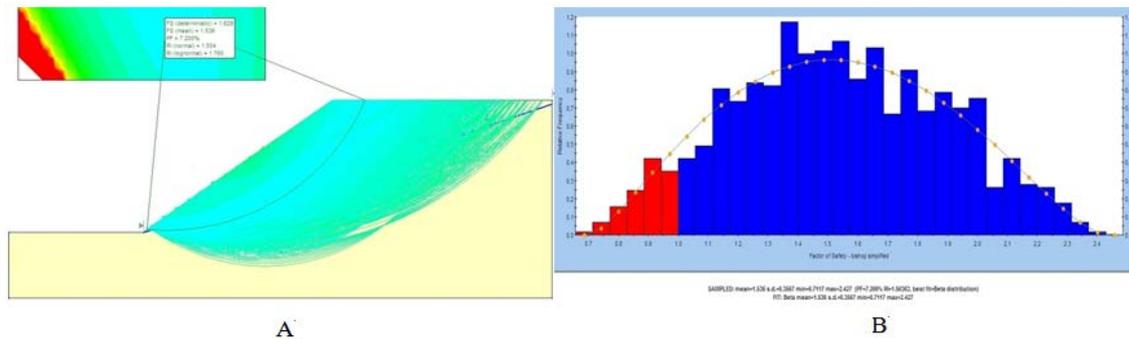


Figure 2. A) LEM simulation for Chandaakarea (Dry). B) FOS (Bishop simplified) v/s Relative frequency Chandaak area (Dry)

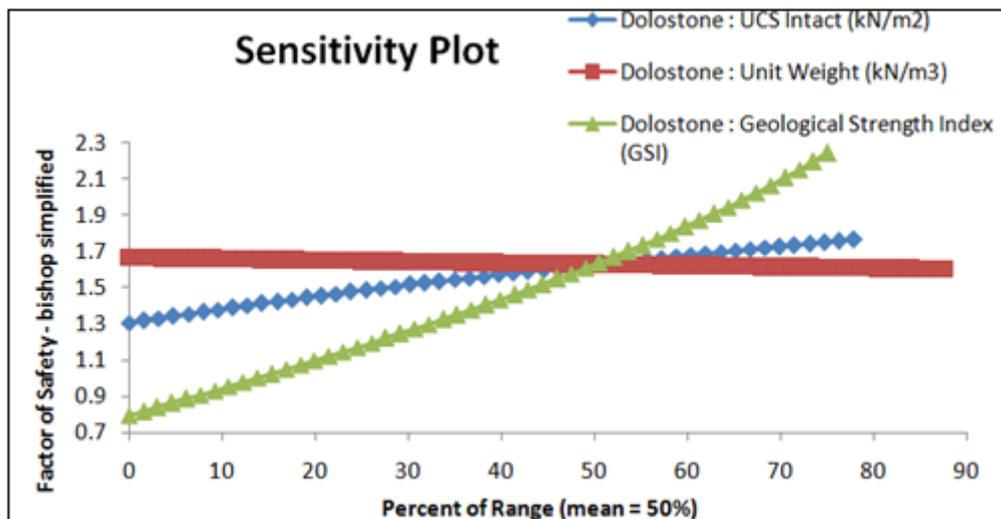


Figure 3. Sensitivity plot chandaak dry

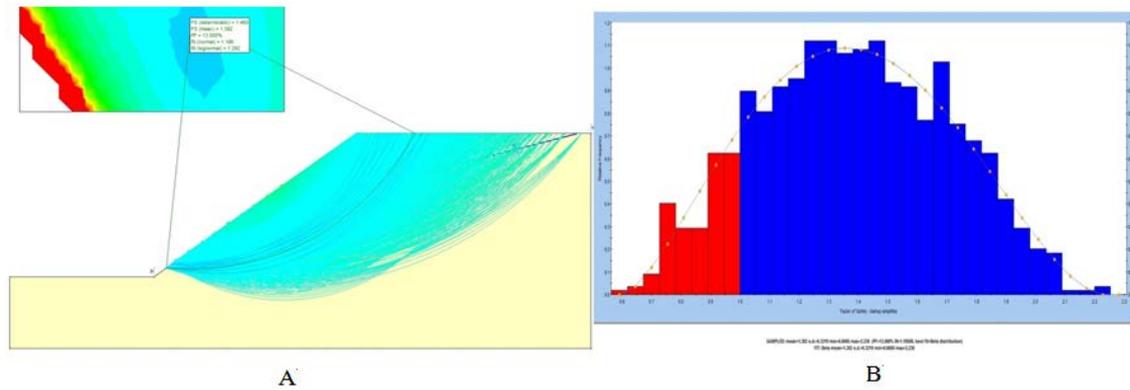


Figure 4. A) LEM simulation for Chandaak area (saturated), B) FOS (Bishop simplified) v/s Relative frequency Chandaak area (Saturated)

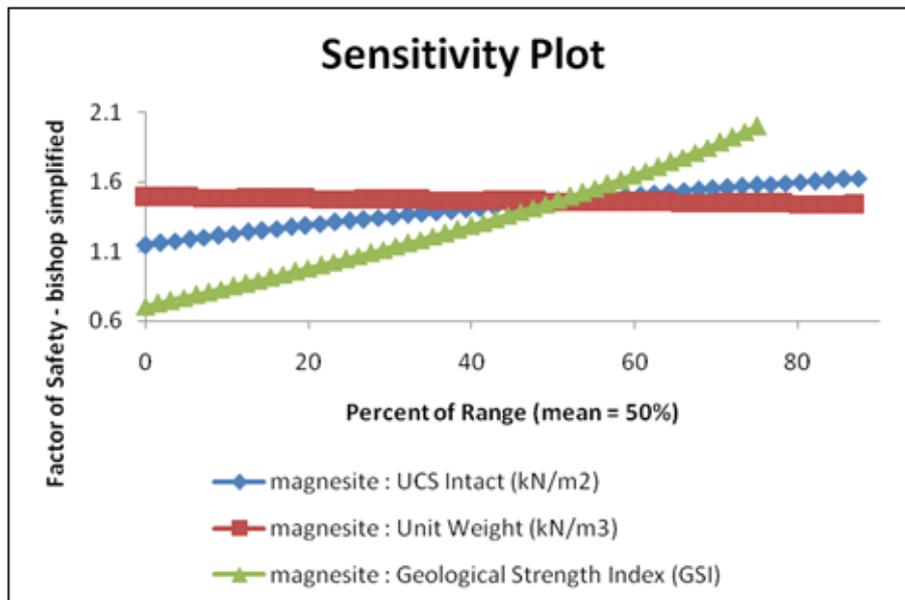


Figure 5. Sensitivity plot Chandaak (Saturated)

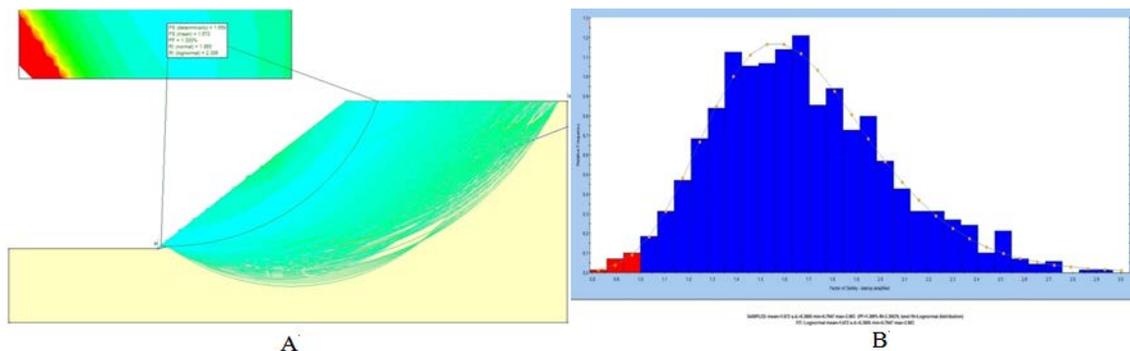


Figure 6. A) LEM simulation for Chhera area (dry), B) FOS (Bishop simplified) v/s Relative frequency Chhera area (Dry)

2.3. Limit Equilibrium Analysis

The two hill slopes, Chandaak and Chhera were analyzed using limit equilibrium method for calculation of factor of safety and probability of failure. At the same time the sensitivity of each parameter on the factor of safety was analyzed. The probability analysis was done using Monte-Carlo simulation which uses randomly selected discrete values of each variable from their probability distribution. A sensitivity analysis indicates which input parameters may be critical to the assessment of slope stability, and which input parameters are less important (Singh et al., [1] and Kainthola [5,6]). A

Sensitivity analysis involves the variation of individual variables between minimum and maximum values and a sensitivity analysis is performed on only one variable at a time while probabilistic analysis uses the values of all the random variables. The factor of safety was calculated using Bishop's method of slice. The analysis was done for both dry and saturated conditions. During the field visit few wet patches and water springs were observed which were used to infer information regarding the ground water condition of the area. The water table was also raised by 2-3 meters for saturated conditions with subsequent reduction in their UCS values (Table 1).

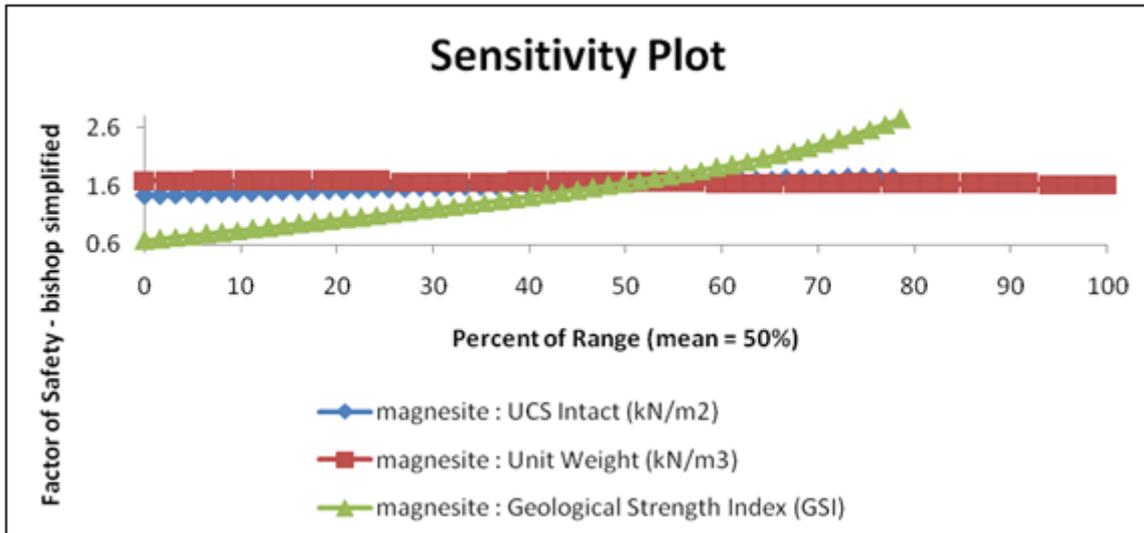


Figure 7. Sensitivity plot Chhera (Dry)

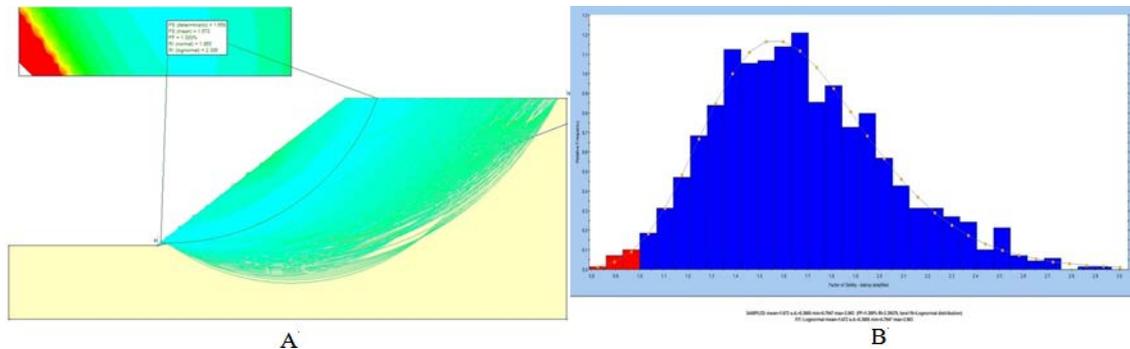


Figure 8. A) LEM simulation for Chhera area (saturated), B) FOS (Bishop simplified) vs Relative frequency Chhera area (saturated)

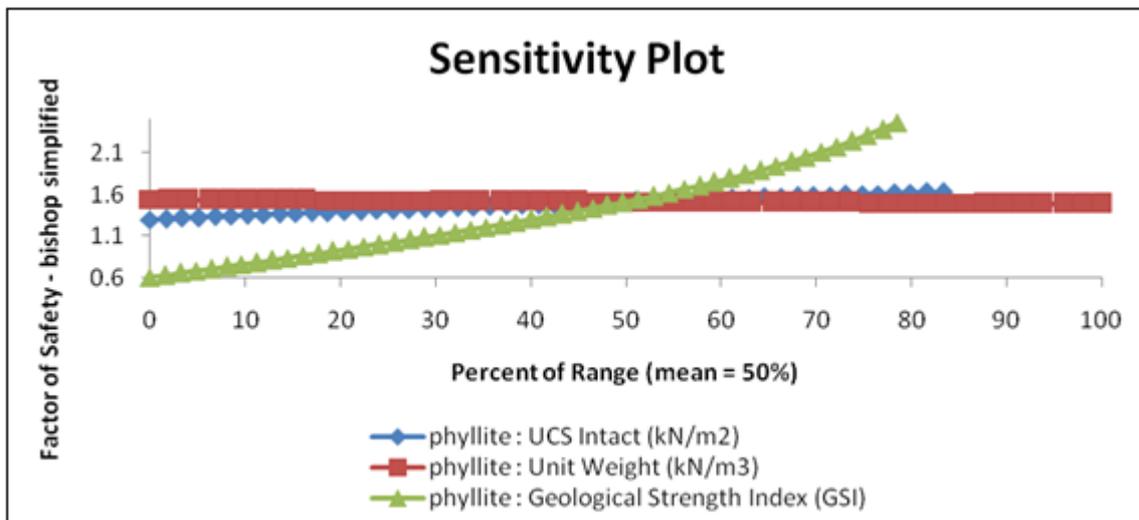


Figure 9. Sensitivity plot Chhera (Saturated)

3. Results and Discussion

The probabilistic analysis is one of the techniques which are being employed to overcome the uncertainties in the stability assessments of both rock and soil slopes. In the probabilistic method, the analysis is carried out on the random properties of the rock mass. Random properties as input parameters have been used for probabilistic analysis

and are obtained by statistical evaluation of available geological and geotechnical data from laboratory as well as field. The results have taken into account the uncertainties of the rock mass. The chandaak hills composed of dolostone had relatively lower strength compared to phyllitic chhera hill. There was a significant reduction in strength parameters under the saturated conditions. For all the test results, GSI values were shown to have been most sensitive with respect to the FOS. While the unit weight of the rock material was least

sensitive towards the FOS. The mean FOS yielded was lower as compared to the deterministic values. The hill slopes of Chandaak area become quite critical under the saturated state (Table 2). The chief attribute for the lowering in strength and factor of safety for the Chandaak area is due to the high porosity of the dolostones which

are rock composed of magnesian and calcium carbonates of sedimentary origin. On the other hand, the reduction in safety factor for Chhera is considerable less as the porosity of phyllites is quite less as compared to dolostones.

Table 2. Results of the probabilistic analysis for the two areas using both Bishop's method and Fellenius method

Hill Slope		Chandaak area (dry)	Chandaak area (saturated)	% Variation	Chhera area (dry)	Chhera area (saturated)	% Variation
Results							
FOS (deterministic)	Bishop's Method	1.629	1.46	10.37446	1.658	1.513	8.745476
	Fellenius method	1.487	1.361	8.473436	1.525	1.390	8.852459
FOS (mean)	Bishop's method	1.536	1.382	10.02604	1.672	1.519	9.150718
	Fellenius method	1.404	1.289	8.190883	1.543	1.339	13.221
Probability of failure (%)	Bishop's method	7.2	13.0	80.5	1.3	3.9	200
	Fellenius method	11.4	19.7	72.8	3.1	7.7	148
Reliability index (normal)	Bishop's method	1.504	1.186	21.14362	1.865	1.582	15.17426
	Fellenius method	1.22	0.951	22.04918	1.577	1.284	18.57958
Reliability index (lognormal)	Bishop's method	1.760	1.292	26.59091	2.306	1.852	19.68777
	Fellenius method	1.342	0.975	27.34724	1.857	1.420	23.53258

The analysis was carried out to get the FOS (deterministic), probability of failure (PF) and reliability index (normal and lognormal) of the hill slope. The probability of failure is described as equal to the number of analyses with safety factor less than 1, divided by the total Number of Samples. Reliability index is also used as a parameter to assess the stability of slopes. The Reliability Index (RI) indicates of the number of standard deviations which separate the Mean Safety Factor from the critical safety factor of 1 (Rocscience [23]). Table 2 depicts the investigation results for the hill slopes under both dry and saturated conditions. It is clearly visible that the FOS, OF and RI values using Fellenius method were lower as compared to the Bishop's method. The lower results may be attributed to the assumptions in the Bishops method. As can be seen from Table 2, the probability of failure (PF) increases by 80.5 and 72.8 percentage from dry to Saturated method using Bishop's and Fellenius method, respectively. While for the Chhera area the PF shows an exceptional increase of 200 to 148 percentage from dry to Saturated method using Bishop's and Fellenius method, respectively, although the hill slope is relatively stable as compared to the Chandaak hill slope. The study also demonstrates that the factor of safety for any analysis yielded by Bishop's methods is higher as compared to the FOS achieved by Fellenius method (Table 2). The values achieved using limit equilibrium method are conservative as compared to finite element methods (Kainthola et al., 2012), hence though the FOS values deem them relatively stable, the slopes are relatively higher probability of failure.

4. Conclusion

In the present investigation two 500m high hill slopes, Chandaak and Chhera in Pithoragarh, lesser Himalaya,

India where small scale mining of magnesite is also taking place, were analyzed for the probability of failure through probabilistic and sensitivity analysis using limit equilibrium method. The Chandaak hill slope is composed of magnesite veins containing dolostone while the Chhera hill slope is predominantly made up of phyllites. In both the hill slopes the rock mass has varied weathering grade, ranging from highly weathered to moderately weathered. The analysis was carried out for both dry and saturated condition accounting for the seasonal variation in the rock mass strength. In the both case i.e in dry as well as saturated, Chhera hill were computed to have higher FOS as compared to the Chandaak hill (Table 2). Also the probability of failure of Chhera hill is very less as compared to Chandaak, which becomes quite critical under saturated conditions. Though the PF of total hill slope collapse is low but the occurrence of local failures can't be denied which have been reported from the area.

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