Journal of Advanced College of Engineering and Management

Pre and Post Earthquake Slope Stability Analysis Using Equivalent Linear Method – A Case Study of Jure Landslide

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Abstract

Slope stability analysis is one of the most important tools to determine the stability of both natural as well as man-made slopes. The main objective of this study is to compare safety factor of the Jure landslide before and after an earthquake occurrence using Geostudio QUAKE/W module. Three different positions of water table (top, middle and bottom of debris) were considered for the study. The safety factors of both deterministic and probabilistic case are determined. The Gorkha Earthquake's time history data were taken into consideration. Both the bedrock and debris are modeled using the equivalent linear approach for dynamic analysis. The findings indicate that the slope was on the verge of failing prior to the earthquake and is predicted to fail following the earthquake event that was taken into account.

Keywords: *Slope Stability, Geostudio QUAKE/W, Equivalent Linear Model, Gorkha Earthquake*

1. Introduction

Nepal experiences a variety of hazards in the form of earthquakes, landslides, floods and other. Among them landslide is one of the most devastating hazard that destroys majority of the population as well as their property every year which is why it is important to determine landslide prone areas in order to provide rectifying measures to protect the population in nearby areas.

Devastating earthquakes are another frequent occurrence in Nepal and these might serve as a catalyst for additional dangers. Hence the effect of earthquake in the slope stability is studied in order to determine the safety factor of the slope when it is subjected to dynamic loading.

There are numerous techniques for determining the slopes' safety under static and dynamic loading (seismic) conditions. Finite element (FEM) approaches are used in some methods while limit equilibrium (LEM) approaches are used in others. Methods like Bishop, Spencer, Janbu etc. use Limit equilibrium approach for determining the safety factor while methods like QUAKE/W, SIGMA/W modules of Geostudio use Finite Element approach for determining the same. Numerical techniques using finite elements are founded on the idea of breaking a continuum into smaller parts, describing the behavior or actions of the individual pieces, and then linking all the pieces to describe the behavior of the continuum as a whole. Discretization or meshing is the process of breaking the continuous into smaller pieces. Finite elements are the name given to the parts. The fundamentals of using a dynamic slope stability analysis using Geostudi QUAKE/W is given below:

1.1 Shear modulus

The term "G_{max}" refers to the shear modulus. It is known as G_{max} because it is the maximum value for a specific soil and is therefore considered to be a small-strain shear modulus. G_{max} is typically defined as a function of the soil's stress status. In general, as confining or overburden stress increases, the soil stiffness rises as well. G_{max} values in QUAKE/W can be provided as functions to capture this behavior.

The original equation given by Kramer (1996) is as follows:

$$G_{max} = 1000\, k\, (\sigma_m)^{0.5} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

This equation is only directly applicable if the mean stress is in units of lb/ft^2. To make the equation workable with all sets of units and yet have the same K value, the Geostudio team has recast the equation as:

For granular soils the sample functions are based on the following equation modified after Kramer(1996):

$$\mathrm{G}_{max} = 22\mathrm{k}\sqrt{P_a * \sigma_m} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where P_a is the atmospheric pressure and σ_m is the mean stress in the same units.

Based on the work by Hardin and Drnevich (1972), Hardin (1978) and Mayne and Rix (1993), the Gmax of cohesive soils can be estimated from:

$$G_{max} = 625\left(\frac{1}{(0.3+0.7e^2)}\right)(OCR)^K\sqrt{P_a * \sigma_m} \ldots\ldots\ldots (3)$$

Where, e is the void ratio, OCR the over-consolidation ratio and k an exponent related to the soil plasticity index PI.

The k exponent is computed from,

$$k = \frac{PI^{0.72}}{50} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

1.2 G Reduction Function

In response to cyclic shear strain, soil subjected to dynamic stresses has a tendency to soften. The Equivalent Linear Soil Model describes this softening as a ratio with respect to Gmax. An example of this is a G-reduction function. The finite element analysis produces the cyclic shear strain. To calculate fresh G values, the function and the provided Gmax are combined with the computed shear strain throughout each cycle.

Ishibashi and Zhang (1993) developed an expression for estimating the G/Gmax ratio. The two main variables are PI (plasticity index) and confining pressure. A summary of expression developed by them is as follows:

$$\frac{G}{G_{max}} = K(\Upsilon, PI)(\sigma_m)^{m(\Upsilon, PI) - m_o} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$K(\Upsilon, PI) = 0.5\left\{1 + \tanh\left[ln\left(\frac{0.000102 + n(PI)}{\Upsilon}\right)^{0.492}\right]\right\} \ldots\ldots\ldots\ldots (6)$$

$$m(\Upsilon, PI) - m_o = 0.272\left\{1 + \tanh\left[ln\left(\frac{0.000556}{\Upsilon}\right)^{0.4}\right]\right\} exp(-0.0145PI^{1.3}) \ldots\ldots\ldots (7)$$

n(PI) = 0.00 for PI = 0

n(PI) = 3.37 x 10^{-6} PI$^{1.404}$ for $0 < \mathrm{PI} < 15$

n(PI) = 7.00 x 10^{-7} PI$^{1.976}$ for $15 < \mathrm{PI} < 70$

n(PI) = 2.70 x 10^{-5} PI$^{1.115}$ for PI > 70

These expressions, together with an assumed range of cyclic shear strains (γ), makes it possible to compute G/Gmax values and produce a function for a specified PI and a specified confining stress.

1.3 Damping Ratio

The damping ratio in QUAKE/W can be defined as a constant or a function. The damping ratio and the G-reduction function are both functions of the cyclic shear strain.

A formula for estimating the Damping Ratio function has been developed as a result of research (Ishibashi and Zhang, 1993). The plasticity index (PI), the G/Gmax modulus reduction ratio, and indirectly the confining pressure are the variables in the expression. The expression is:

$$\xi = 0.333\frac{1+\exp(-0.0145PI^{1.3})}{2}\left[0.586\left(\frac{G}{G_{max}}\right)^2 - 1.547\frac{G}{G_{max}} + 1\right] \ldots\ldots\ldots\ldots (8)$$

Based on the provided PI and confining pressure, the G/Gmax ratio is calculated as explained above. After that, the Damping Ratio is calculated using the same PI and an expected range of cyclic shear strains. The Damping Ratio function is then developed using the obtained data points.

1.4 Probabilistic Slope Stability Analysis

The probability of failure resulting from variations in material qualities, pore-water pressure conditions, surcharge and point loads, and reinforcing parameters can be described using a probabilistic analysis in Geostudio. The effect of uncertainty on the accuracy of slope design and performance evaluation is frequently substantial. Because uncertainty cannot be clearly addressed in conventional slope practice based on the factor of safety, forecasts are not as accurate as they could be. Probabilistic methods are logical ways to express uncertainty in slope analysis and design and to quantify it. A probabilistic method of investigating geotechnical problems provides a methodical technique to handle uncertainties, particularly slope stability. Uncertainties can be quantitatively attributed to the slope's design reliability in terms of probability.

1.5 Gorkha Earthquake

The time history data considered in this study is of Gorkha earthquake. On April 25, 2015, at 11:56 AM, the Gorkha earthquake with moment magnitude (Mw) 7.8 (USGS) and local magnitude 7.6 (National Seismological Center) occurred (local time). Since the 1934 Nepal-Bihar earthquake (Mw 8.2), this earthquake was among the strongest to ever hit Nepal. Due to its vulnerable geological position and high ground water recharge, Sindhupalchowk, where the Jure landslide occurred, is one of the districts that were most severely hit by this earthquake. The time history plot of this earthquake is presented below:

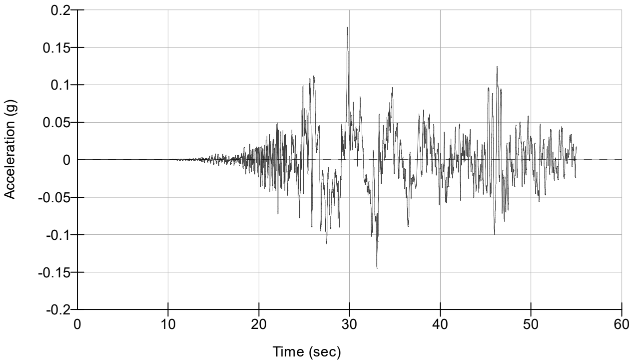


Figure 1- Time History Plot of Gorkha Earthquake (2015)

2. Study Area

The study area is located in Sindhupalchowk distict of Nepal. It is located 70 km to the northeast of Kathmandu Valley between latitudes of 27°45'19.75" and 27°47'29.75"N and longitudes of 85°54'15.37" and 85°51'39.77"E. The study region has a generally mountainous topography with a river running through it. The area is traversed by the Araniko highway, which runs alongside the Sunkoshi River and connects to the Chinese border at Kodari. It has a subtropical, temperate, and alpine climate. The range of temperatures is 28.5° to 4.0° C, and there is 3604.3 ml of rainfall, of which 80 percent falls during the monsoon season (Nepal Tourism Board 2008). The Kuncha formation, which is composed of fine-grained quartz-conglomerates, phyllitic quartzites and meta-sandstones, and rare basic rock types, is part of the region's highly active geology (amphibolitic) volcanic layers. The region has had numerous large landslides at various points in time.

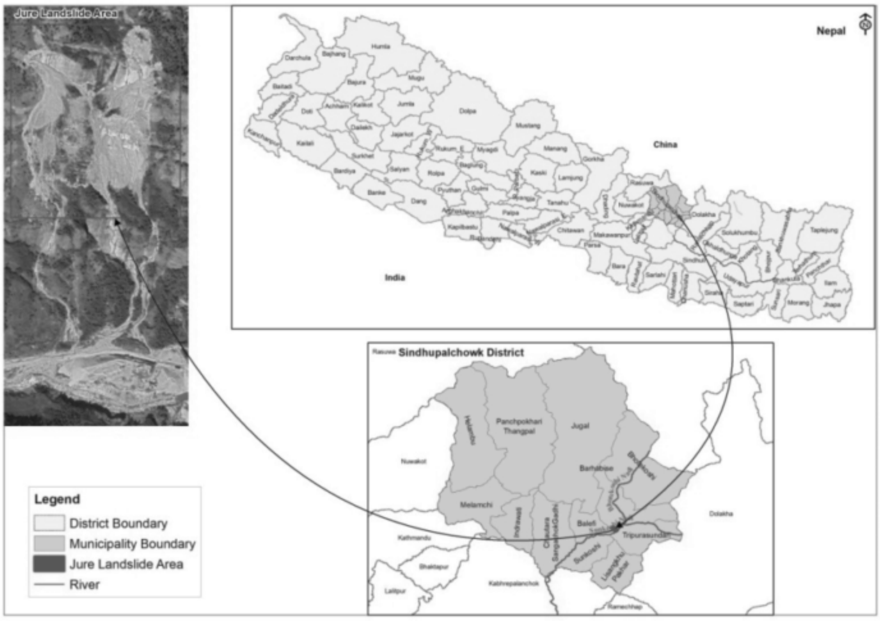


Figure 2- Landslide Area

3. Methodology

Desk research on pertinent articles based on the Jure landslide forms the basis of the research. The area's contour maps are correctly examined, and the geology, climatology, and seismicity of the landslide area are investigated. The entire geological and geotechnical data is gathered at the site. To determine the soil shear strength parameter, a direct shear test is conducted. AutoCAD is used to prepare the slope profiles. Sections namely Section 1-1, Section 2-2 and Section 3-3 are prepared using SW-DTM software along with the detail topographical map of the site. A 2D plain strain problem is used to represent the slope profiles. The modeling of the slope along with the analysis is done in Geostudio QUAKE/W module. The discretization and meshing is done with the combination of 4 noded quadrilateral and 3 noded triangles.

Equivalent Linear Model is used to model both debris and the bedrock in order to establish both static and dynamic stress condition. The soil and the rock properties used for the analysis are as follows:

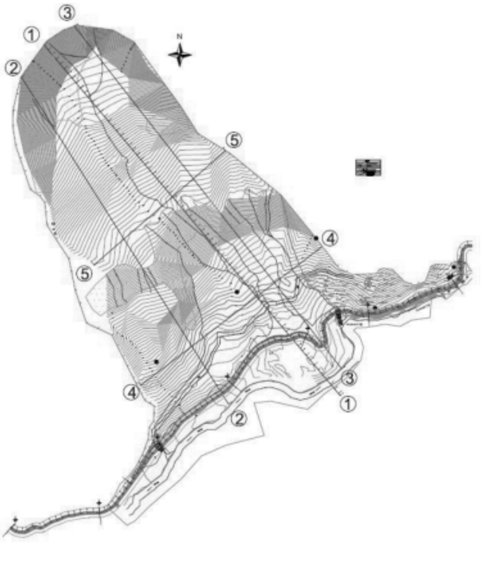


Figure 3- Contour map of Jure Landslide Area

Table 1-Parameters Used for Slope Stability Analysis (Dry Case)

Material	Material Model	Unit Weight (KN/m³)	Shear Strength Parameters		Poisson's Ratio
			Cohesion (Kpa)	Friction Angle(Degree)	
Dry Soil	Mohr-Coulomb	18	5	32	0.3

Table 2-Parameters Used for Slope Stability Analysis (Saturated Case)

Material	Material Model	Unit Weight (KN/m³)	Shear Strength Parameters		Poisson's Ratio
			Cohesion (Kpa)	Friction Angle(Degree)	
Saturated Soil	Mohr-Coulomb	21.7	6.75	28.55	0.3

Table 3-Parameters Used for Slope Stability Analysis (Schist Interbedded with Phyllite)

Material	Material Model	Unit Weight (KN/m³)	Shear Strength Parameters		Poisson's Ratio
			Cohesion (Kpa)	Friction Angle(Degree)	
Schist Interbedded with Phyllite	Bed Rock (Impenetrable)	27	-	32	0.3

The material model for thus prepared with the help of these above mentioned parameters for slope 1-1 is given below:

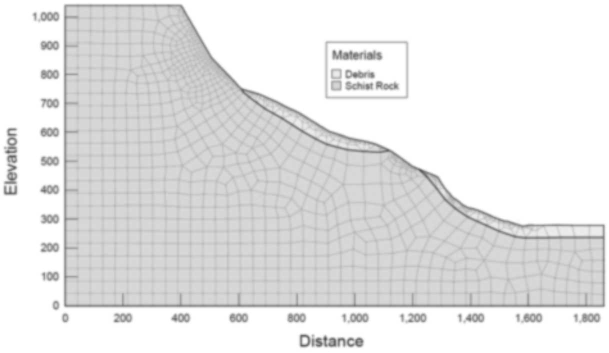


Figure 4-Material Model with mesh for Section 1-1

The G-reduction function was established for a confining stress of 100Kpa and Plasticity Index (PI) of 6.7 for debris and a confining stress of 100Kpa for the bedrock. The resulting G-reduction function thus obtained is as shown in the figure:

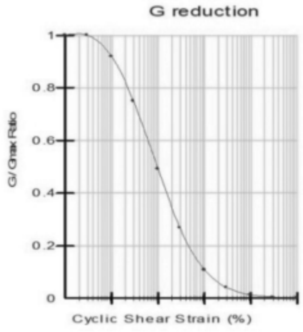


Figure 5- G-Reduction function

The Pore Water Pressure (PWP) function was established considering an N-exponent of 0.7 for debris. The resulting PWP function obtained is given below:

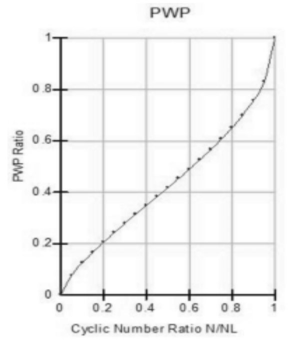


Figure 6- PWP function

The Cyclic Number function was established considering the debris to be loose sand. The resulting Cyclic Number function thus obtained is given below:

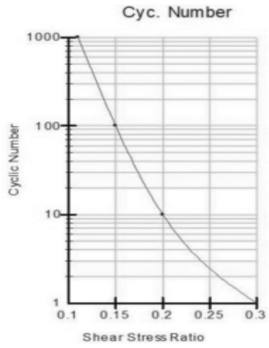


Figure 7- Cyclic Number function

The function for the damping ratio is established using the confining ratio of 100Kpa and a Plasticity index of 6.7 for debris and a confining pressure of 100Kpa for bedrock. The resulting Damping Ratio function thus obtained is given below:

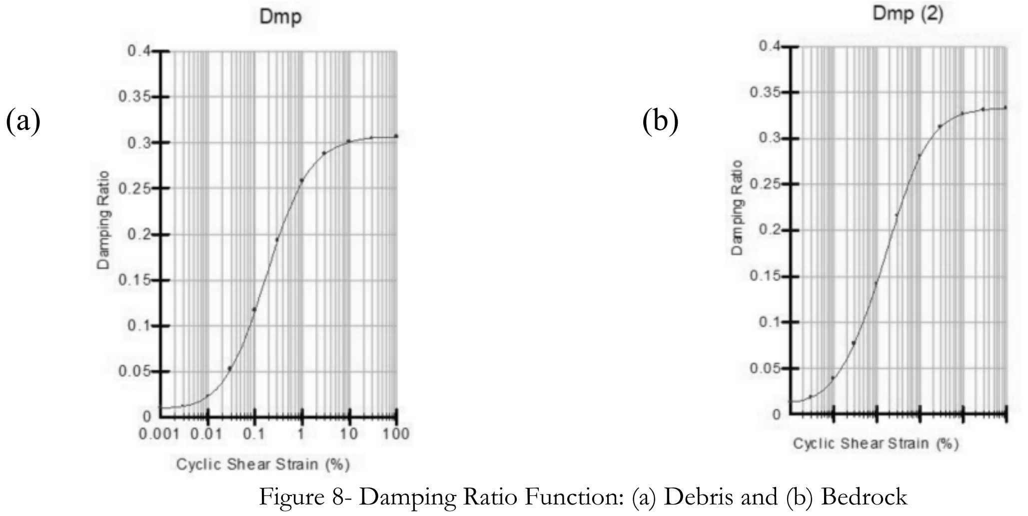


Figure 8- Damping Ratio Function: (a) Debris and (b) Bedrock

The G_{max} function is established considering the debris to be loose sand and considering the bedrock to be dense gravel. The resulting G_{max} function thus obtained is given below:

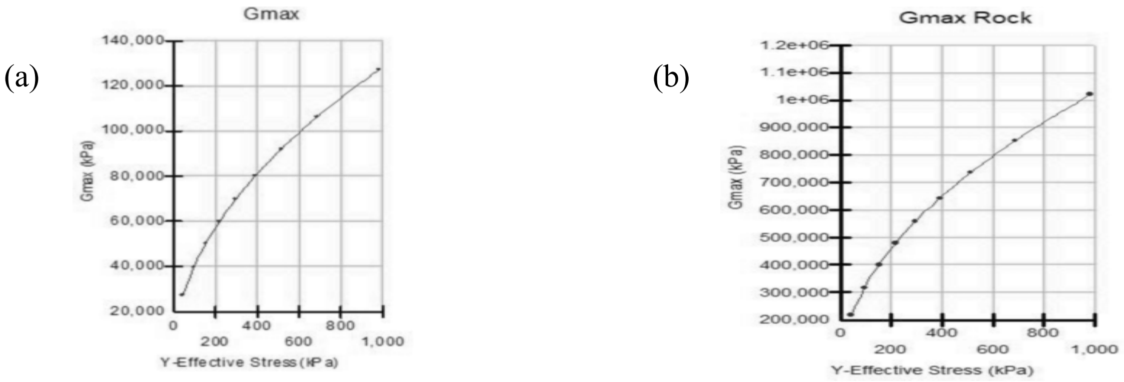


Figure 9- G_{max} function: (a) Debris and (b) Bedrock

Probabilistic Slope Stability Analysis

For probabilistic approach, the number of Mont. Carlo Simulation trials is taken as default value of Geostudio i.e. 4521. A normal distribution type of function is used for the analysis. The range of cohesion values are taken from 0 – 10 Kpa and the range of angle of friction is taken from 27` – 37`. The Probability Density Function and the sampling function are presented below:

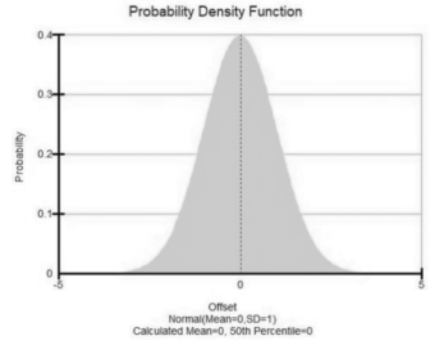


Figure 10: Probability Density Function

4. Results and Discussion

The factor of safety is determined for all three slope sections which are presented in table below. The water table is placed at the bottom, middle and top of the debris to determine the safety factors. Both the deterministic and probabilistic safety factors are determined for these three sections. The results obtained are presented in table below:

Table 4- FoS Obtained for different cases when Water Table is at the Bottom of Debris

Section	Pre Earthquake Stability		Post-Earthquake Stability	
	Deterministic	**Probabilistic**	**Deterministic**	**Probabilistic**
1-1	0.973	0.905(P=99.45%)	0.801	0.811(P=100%)
2-2	1.085	1.086(P=1.99%)	1.024	1.038(P=16.34%)
3-3	1.030	1.017(P=34.1%)	0.868	0.870(P=99.7%)

Table 5- FoS Obtained for different cases when Water Table is at the Middle of Debris

Section	Pre Earthquake Stability		Post-Earthquake Stability	
	Deterministic	**Probabilistic**	**Deterministic**	**Probabilistic**
1-1	0.727	0.745(P=100%)	0.460	0.477(P=100%)

2-2	0.744	0.742(P=100%)	0.650	0.649(P=100%)
3-3	0.671	0.668(P=100%)	0.495	0.497(P=100%)

Table 6- FoS Obtained for different cases when Water Table is at the Top of Debris

Section	**Pre Earthquake Stability**		**Post-Earthquake Stability**	
	Deterministic	**Probabilistic**	**Deterministic**	**Probabilistic**
1-1	0.528	0.503(P=100%)	0.373	0.374(P=100%)
2-2	0.541	0.507(P=100%)	0.474	0.475(P=100%)
3-3	0.630	0.616(P=100%)	0.413	0.417(P=100%)

i. When water table is at the bottom of debris

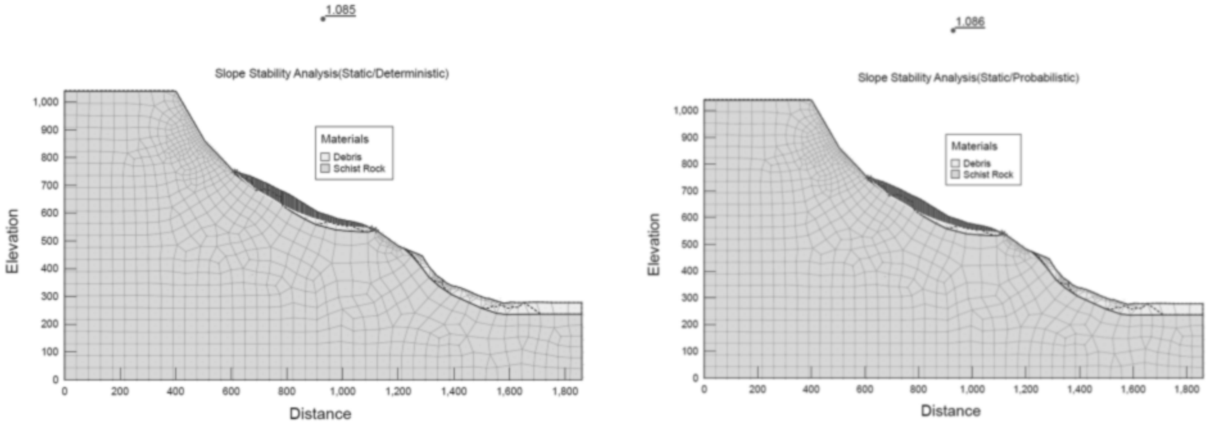
The factor of safety tends to be the highest for this case. The results indicate that the sections 2-2 and 3-3 are stable (FoS>1) before the dynamic stress during earthquake is applied with the probability of 1.99% and 34.1% respectively. However, slope 1-1 is at the verge of failure with the safety factor of 0.973 before the application of any dynamic stresses. The results further indicate that the safety factors tend to decrease by 13% in average after the application of dynamic stresses during earthquake.

ii. When water table is at the middle of debris

The results indicate there is further decrease in the safety factor when the position of the water table is altered to the middle of debris. All three sections considered are unstable (FOS<1) with the probability of occurrence of 100%. The safety factors tend to decrease further after the application of dynamic stresses due to earthquake. The results further indicate that the safety factors tend to decrease by approximately 25% in average after the application of dynamic stresses during earthquake.

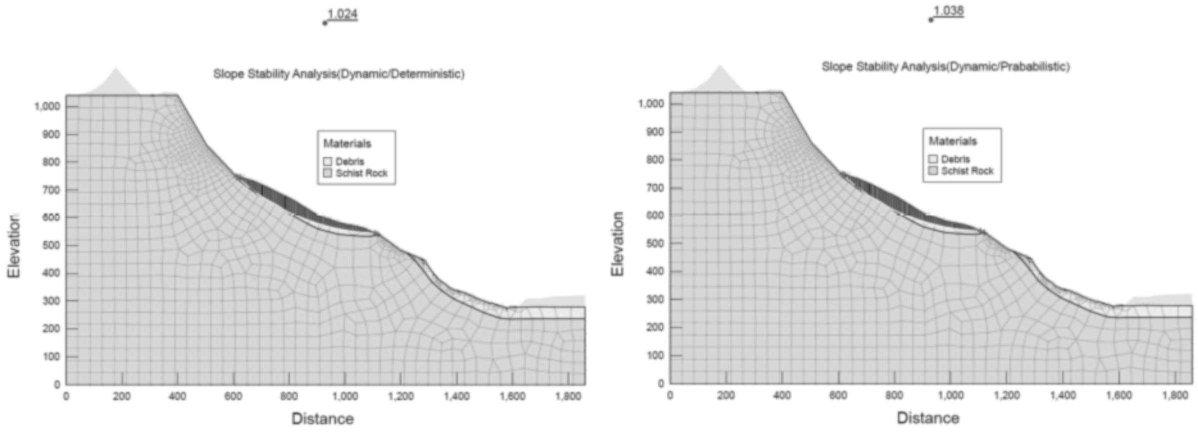
iii. When water table is at the top of debris

The results indicate there is further decrease in the safety factor when the position of the water table is altered to the top of debris All three sections considered are unstable (FOS<1) with the probability of occurrence of 100%. The safety factors tend to decrease further after the application of dynamic stresses due to earthquake. The results further indicate that the safety factors tend to decrease by approximately 25% in average after the application of dynamic stresses during earthquake.



(a) (b)

Figure 11-Slope Stability Analysis of Section 2-2 when WT is at the Bottom of Debris: (a) (Static/Deterministic) (b) (Static/Probabilistic)



(a) (b)

Figure 12-Slope Stability Analysis of Section 2-2 when WT is at the Bottom of Debris: (a) (Dynamic/Deterministic) (b) (Dynamic/Probabilistic)

5. Conclusion

Slope failures have frequently happened in the studied area in the past, which has resulted in the occurrence of catastrophic natural calamities. The latest catastrophic event happens to have occurred on 2nd August 2014. The Gorkha Earthquake occurred on 2015 such that the slope must have further faced reduction in the strength. Hence, the slope has to be analyzed on regular basis such that the number of fatalities can be decreased to a great extent. Mitigation measures can also be designed in order to prevent these events in further days.

From the analysis of slope before and after an earthquake event using Equivalent Linear Model, following conclusions are made: 1) The slope is found stable (FOS>1) for sections 2-2 and 3-3 when the water table is placed at the bottom of the debris before earthquake. 2) All the other slopes are found unstable (FOS<1) before earthquake even when the position of water table is altered. 3) Every slope section is found unstable after the earthquake event even when the position of water table is altered.

There is a high likelihood that this landslide may fail if a similarly strong earthquake strikes Nepal again, which could lead to other catastrophic catastrophes.

Acknowledgement

The authors are thankful to the co-ordinator of Department of Geo-Technical Engineering, Pulchowk Campus. The authors are thankful to Mr. Uddhav Lal Karki and Mr. Smaral Dahal for providing assistance related to the use of ArcGis.

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