Stability assessment of a soil slope in Meghalaya, north-eastern India

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Abstract. Landslides are a common occurrence in hill slopes in the seismically active north eastern part of India. The soil slopes are highly vulnerable to failure due to heavy earth cuttings, rainfall and blasting activities during road construction. When landslides occur in transportation corridors running along hill slopes, there is the risk of huge loss to lives and property. In addition, the communication through these networks could be brought to a standstill during such catastrophes, resulting in considerable amount of time and resources expended in restoration of traffic and causing huge inconvenience to commuters. In this scenario, the need arises for a proper investigation on failure mechanisms of hill cut soil slopes and to envisage on appropriate mitigation measures. In the present study, stability analysis is carried out of in-situ soil slopes newly exposed during a road widening along National Highway-40, a strategic road corridor in Meghalaya. The analysis consists of a limit equilibrium approach wherein the slope has been modelled using in-situ soil conditions. The factors of safety of the slope against sliding failure have been calculated and the critical slip surface has been found by limit equilibrium analysis. The results of numerical modelling using the commercially available software SLOPE/W indicates unstable slopes potentially vulnerable to failure under adverse conditions. Necessary mitigation measures that need to be taken have been suggested based on the vulnerability condition of the slope.

Keywords: slope stability; landslides; limit equilibrium analysis; factor of safety; Meghalaya

1 Introduction

Landslide is a geological phenomenon where a mass of earth slides or moves due to the loss in its stability in instances characterized by steep or gentle slope gradients. The main cause of landslides which affect the stability of slope is the gravity force. But generally, landslides occur due to the triggering by some other event such as – incessant rainfall, earthquake, etc. Nowadays landslides have become common along the highways and rail lines where natural hill slopes are cut and disturbed during the road and railway track construction. In the north-eastern part of India landslides in this scenario are triggered by heavy rainfalls during the monsoon due to which the main national and state highways and the railway lines are blocked.

Two of the major landslides seen in this region in the recent years that disrupted the road and rail connectivity are mentioned herewith:

1) Landslide incidence along Lumding–Badarpur Railway Line, Dima Hasao district, Assam (14 June 2018) - Incessant rainfall from 12th to 14th June 2018 triggered landslides blocking the Lumding–Badarpur railway service in Dima Hasao district of Assam. A high 382 mm of rainfall was recorded on 14.06.2018 which triggered four landslides between 2:00 PM and 3:00 PM along the Lumding–Badarpur Railway Line. The Bandarkhal landslide, located between Bridge No. 305 and Tunnel No. 19 led to the suspension of railway service in the Lumding–Badarpur line for three consecutive days [1].

2) Landslide incidence at Sonapur, East Jaintia Hills District, Meghalaya - On 7th May 2018 (01:00hrs), heavy rainfall triggered few landslides along NH-6 connecting Shillong with Barak Valley of Assam, Mizoram and Tripura which blocked 10m stretch of the important road corridor for more than 12 hours [2].

Due to such severity of the landslides it is necessary to conduct a detailed slope stability analysis of the area both before and after the construction of roadways and railways so that the best method of prevention, control and stabilization can be suggested and implemented.

1.1 Background of the study.

Analyzing the stability of earth structures is the oldest type of numerical analysis in geotechnical engineering. The idea of splitting a potential sliding mass into slices was introduced early in the 20^{th} century and has gained significance in slope stability analysis problems around the world. The stability analysis of the Stigberg Quay in Gothenberg, Sweden was studied where the slip surface was taken to be circular and the sliding mass was divided into slices [3]. In the next few decades, the scope of the method was expanded, and the Ordinary or Swedish method of slices was introduced. Further advancement in terms of application of circular slip surfaces and use of composite slip circles etc. were developed in this method in the mid-1950s [4,5]. In 1965, a new technique was developed based on mathematically more rigorous formulations [6]. The reason for the limit equilibrium method being adopted so readily, is that solutions could be obtained by hand-calculations. Simplifying assumption had to be adopted to obtain solutions, but the concept of numerically dividing a larger body into smaller pieces for analysis purpose was rather novel at the time.

The method of slices was initially believed to be true for slices where the normal stress along the sliding surface is primarily influenced by gravity. However, including reinforcement in the analysis makes its use far beyond intended intentions. While modern software is making it possible to analyze ever–increasingly complex problems, the same tool is also making it possible to better understand the limit equilibrium method itself. Computer assisted graphical viewing of data used in calculations makes it possible to look beyond the factor of safety. Salient features of

Limit Equilibrium method are: (1) It satisfies force and moment equilibrium due to resisting and driving force on each slide. (2) For stable slope, the factor of safety is greater than 1. (3) Solution techniques differ on how equilibrium conditions are satisfied between interslice shear & interslice normal forces. (4) Solution technique differs in handling interslice shear forces for example Spencer method: constant function, Morgenstern-Price method: half sine, clipped sine, trapezoidal or user defined etc. (5) the slip surface shape is either arc, polygonal or composite [7-11]. A brief summary of the LEM analysis methods is provided in Table 1.

Table 1. LEM Analysis Methods [4-7]

Method	Strength	Weakness
Bishop (1955)	Short analysis time Applicable to Arc/Polygonal	Inaccurate results when horizontal force is acting.
Janbu (1954)	Short analysis time Suitable for shallow slopes	More conservative results
Spencer (1967)	Applicable to Arc/Polygonal More accurate safety factor	Longer analysis time More sensitive convergence
Morgenstern and Price (1965)	Predictable internal normal Force More accurate safety factor	Longer analysis time More sensitive convergence
Sarma (1973)	Suitable for rock slope analysis More accurate safety factor	Longer analysis time & more sensitive convergence. Assumptions for cohesion and friction angle.

Finite Difference Method:

The finite difference method is an approximate method which is used for solving partial differential equations. It is used for solving a wide array of problems including linear and non-linear, time dependent and independent problems and their analysis. It also applies to problems with different boundary shapes, boundary conditions and for a region containing a large no. of different materials. With the development of high-speed computers having large scale storage capability, many numerical solution techniques appeared for solving partial differential equation. However, due to the ease of application of the finite difference method, it is still a valuable means of determining the factor of safety and slope stability. The FLAC/Slope is a software which is based on finite difference method. Salient features of Finite difference Method are as follows, (1) Precise analysis method. (2) Iterative analysis. (3) The slope to be analysed is divided into several zones and each zone is analysed separately. (4) Simulates actual slope failure mechanism. (5) Both stress and strain conditions are satisfied [13].

Contrast between Finite difference method and Limit Equilibrium method:
The difference between finite difference method (numerical method) and limit equilibrium method is that, in finite difference analysis, the slope to be analyzed is divided into a finite number of zones or elements and characteristics of solution is representative of the natural evolution of the physical failure plane in the slope because they satisfy both of stress and strain (kinematics) but limit equilibrium methods satisfies only stress. A comparison between the characteristics of Finite difference and Limit Equilibrium methods in solving for the factor of safety of slopes was done and was concluded that continuum mechanics based numerical methods have the following advantages: (1) No pre-defined slip surface is needed. (2) The slip surface can be of any shape. (3) Multiple failure surfaces are possible. (4) No statistical assumptions are needed. (4) Kinematics (stress and strain) is satisfied [14].

1.2 Description of the site.

An observational study was carried out along a stretch of highway along the NH-6 (previously named as NH-40) [15]. The cut-slope was analysed using the finite difference method and was found to be vulnerable. This paper analyses the stability of the slope using limit equilibrium method. The key characteristics of the site of study have been pointed out below.

Study area.

The study was carried out along a stretch of the along a stretch of highway along the NH-6 (previously named as NH-40) extending from Barapani and Jyntru village, Meghalaya. The area has a tough hilly terrain where the inclination of the slopes extends from being less than 10 to about 56 .

Geological composition.

The slopes which were modelled had rocks of the Shillong Group and were basically meta-sediments, gneiss and granite.

Soil Properties.

Based on the experiments conducted, the various important findings were as follows –

a) Significant amount (> 65%) of silt and clay particles were present.
b) Soil was highly plastic.
c) Natural moisture content (NMC) > optimum moisture content (OMC).

The various geotechnical properties used in this paper for modelling in SLOPE/W software are mentioned in the table (Table 1) below.

Table 2. Geotechnical properties of soil used in the modelling (after [15])

Parent rock	Maximum wet density (g/cm3)	Cohesion (kPa)	Angle of internal friction ( )
Meta-sediments	1.95	17.85	24
Gneiss	2.00	19.22	26
Granite	2.073	20.8	27

The maximum wet density was used in the model as it was seen that in the site of the study rainfall is predominant almost throughout the year, experiencing high to very high rainfall from the months of April to October [15]. During this time landslides are seen to occur the most as the slopes remain very wet throughout the day. To get the most critical result, thus, the authors have used the maximum wet density.

Geometry of slopes.

Four varying slopes were identified and modelled using LEM. The physical dimensions and geometry of the slopes are mentioned below in Table 2.

Table 3. Geometry of soil slopes (after [15])

Parent rock	Slope height (m) and slope angle ( )	
	Cut slope	Natural slope
Meta-sediments	25 m, 50	15m, 20
	18 m, 55	10m, 15
Gneiss	15 m, 60	5 m, 25
Granite	15 m, 50	2 m, 5

The present study aims to assess the vulnerability to sliding of a newly exposed in-situ soil slope along National Highway-40 in Meghalaya using the Limit Equilibrium analysis. The properties of the soil and the slope have been listed above, and the methodology applied is discussed herewith.

2 Methodology:

The modelling of the concerned hill slopes was done in the software SLOPE/W of Geostudio-2019 [12] student edition. SLOPE/W software analyses the slope stability by satisfying the equations of statics and thus the Limit Equilibrium Formulations. The general limit equilibrium formulation comprises of two factors of safety, one of which is derived by equating moments and the other by equating internal shear forces between the slices. Out of the several methods for computing factor of safety, Morgenstern-Price method was chosen as it computes the factor of safety by satisfying both moment and force equilibrium.

The general factor of safety equation with respect to moment equilibrium is:

$$F_m = \frac{\sum(c'\beta R + (N - \mu\beta) R \tan\tan \emptyset')}{\Sigma W x - \Sigma N f \pm \Sigma D d} \quad (1)$$

The factor of safety equation with respect to horizontal force equilibrium is:

$$F_f = \frac{\sum(c'\beta \cos\cos\alpha + (N - \mu\beta)\tan\tan \emptyset' \cos\cos\alpha)}{\Sigma N \sin\sin\alpha - \Sigma D \cos\cos\omega} \quad (2)$$

Where,

c' is the effective cohesion, $\emptyset'$ is effective angle of friction, μ is the pore-water pressure, *N* is the slice base normal force, *W* is the slice weight, *D* is the concentrated point load, *β, R, x, f, d* and *ω* are geometric parameters and *α* is the inclination of slice base

An equation was proposed to relate the interslice shear forces to the normal forces [6], which is-

$X = E\lambda f(x)$
where:
f(x) = interslice shear function,
λ = the percentage (in decimal form) of the function used,
E = the interslice normal force, and
X = the interslice shear force.

The choice of the interslice shear function is one of the major differences between the methods of computing factor of safety. Among these, only the Morgenstern-Price method (M-P method) gives the users the freedom of selecting interslice shear function. This present study considers half sine function for the M-P method in this study as the half sine function tends to concentrate the interslice shear forces towards the middle of the sliding mass and diminishes the interslice shear in the crest and toe areas. M-P method computes the required factor of safety for the slopes by satisfying both Equation 1 and Equation 2 through several iterations.

2.1 Numerical Modelling:

Four hill slopes were modelled in the SLOPE/W software by maintaining the geometrical parameters of the hill slopes given in Table 2. General procedure and guidelines of the software was followed during modelling. Some assumptions were taken in the modelling are: 1) The width of the four-lane highway (NH-6, previously called as NH-40) passing by the slopes was taken to be 23.5 m which is in accordance with the guidelines of Indian Road Congress, 2) The maximum wet density was used in the model as it was seen that in the site of the study, rainfall is predominant almost throughout the year, experiencing high to very high rainfall from the months of April to October. During this time, landslides are seen to occur the most as the slopes remain very wet throughout the day. To get the most critical result, thus, this study considers the maximum wet density, 3) The pore water pressure conditions were chosen to be given by the piezometric line. But, the slopes to be modelled were hill slopes and hence the water table lies at a great depth.

3 Results and Discussions:

The present study deals with the stability investigation of road cut hill slopes along NH-40 in Meghalaya, India. These exposed soil slopes were analysed by Morgenstern-Price method based on LEM. The four soil slope profiles with landslide events were analysed for stability using the strength properties of soil determined at its optimum moisture content. The Factor of Safety (FoS) values for the slopes has been found out to be in the range of 0.821 to 1.147. First two soil slopes from meta-sediments rock type of Shillong Group (Fig. 1,2) gives FoS values of 0.821 and 0.86 respectively which indicates complete instability at maximum wet density of the existing soil. Maximum shear resistance of the critical slip surfaces of these two slopes are found out to be 62.85 kPa and 59.82 kPa respectively. The soil mass of both slopes was oversaturated because of heavy and prolonged rainfall during the period which results in the loss of shear strength of the soil mass. The third slope near Karbalu village consisting of gneiss as parent rock gives FoS value of 0.903 indicating complete instability. The maximum shear resistance of circular failure surface is 64.73 kPa. The Jyntru village slope comprised of granite-based rock has a FoS of 1.147, which indicates that the shear resistance is greater than the maximum shear stress on the critical slip surface. The value of maximum shear resistance of the critical failure surface of the slope is around 61 kPa. The main reason behind the increased FoS of the fourth slope is seemed to be the lesser inclination of the natural slope above the cut slope, which implies lesser impact of gravity force in the direction of the slip surface. Although the FoS value of the fourth slope is greater than 1, but it is still not acceptable as per the standard guidelines of slope stability which suggests minimum FoS value of 1.25 [16]. The impending failure mode of all the four slopes is found out to be toe failure with circular failure surface. Table 3 sums up the results found out from the present analysis.

Table 4. Results of the stability check of the concerned hill slopes from this study

Parent rock of slope	Factor of Safety (FoS)	Maximum shear resistance of slip surface (kPa)	Impending failure mode	Stability
Metasediments 1	0.821	62.85	Toe	Unstable
Metasediments 2	0.86	59.82	Toe	Unstable
Gneiss	0.903	64.73	Toe	Unstable
Granite	1.147	61.00	Toe	Stable

Table 5. Results of the stability check of the concerned hill slopes (after [15])

Parent rock of slope	Factor of Safety (FoS)	Maximum shear strain rate	Stability
Metasediments 1	0.39	4.5×10^{-8}	Unstable
Metasediments 2	0.22	4.5×10^{-4}	Unstable
Gneiss	0.26	8.0×10^{-4}	Unstable
Granite	0.47	4.25×10^{-6}	Unstable

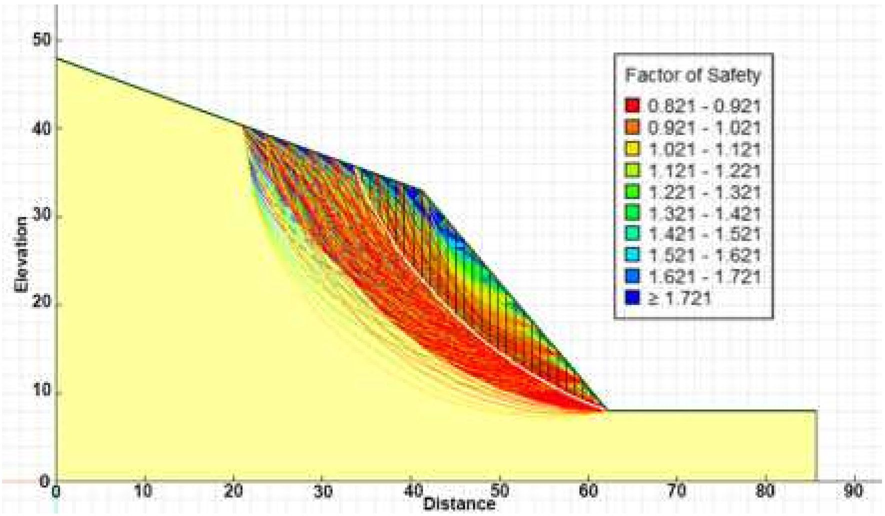

Fig. 1. Slip surfaces of slope 1 (metasediments)

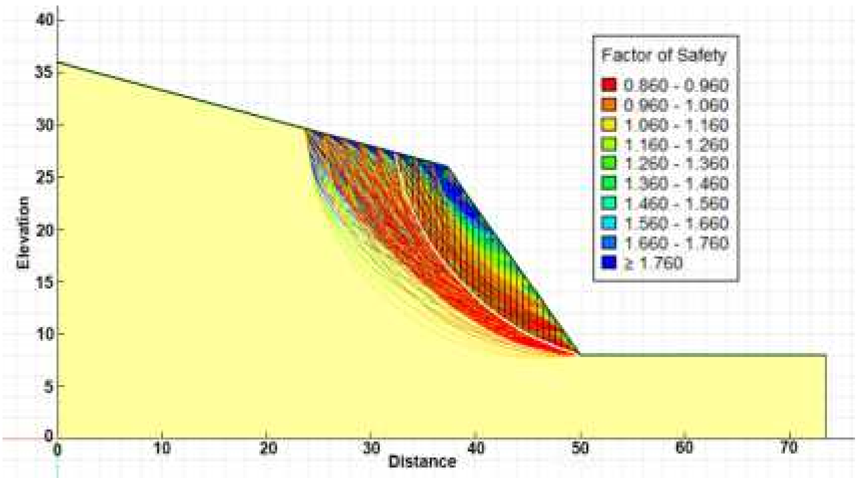

Fig. 2. Slip surfaces of slope 2 (metasediments)

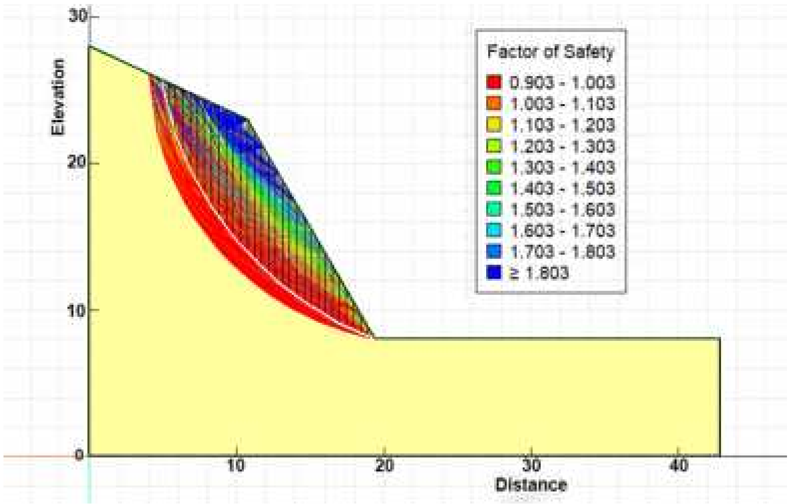

Fig. 3. Slip surfaces of slope 3 (gneiss)

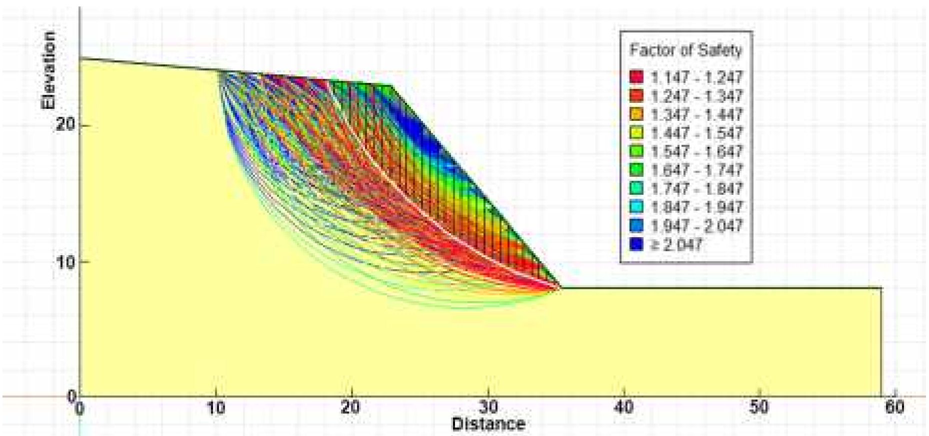

Fig. 4. Slip surfaces of slope 4 (granite)

Note: The white line in Fig 1,2,3 and 4 signifies the critical slip surface.

4 Conclusion:

The main objective of this study was to compare the results obtained from the investigation of the hill cut slopes along NH-6 (previously called as NH-40) in India, where Finite Difference Method (FDM) was used for the analysis [15] with the results obtained using Limit Equilibrium Method (LEM). It is necessary to validate the results LEM because it is a widely known method – the concept of which is properly known even to students who have just started learning geotechnical engineering. Moreover, the results in LEM satisfy only the stress characteristics but FDM, which is a numerical method satisfies both stress and strain characteristics. So, it becomes necessary to compare both the results. The FoS, maximum shear resistance and the impending failure mode were found out using the SLOPE/W software. The results obtained from this study is almost following the same trend of slope instability as obtained by FDM method with fourth slope being an exception as the FoS for that slope has come out to be greater than one. The results obtained is signifying a dangerous scenario of impending slope failure of the concerned hill cut slopes which necessities the importance of a detailed slope stability analysis before expanding or constructing any roads through hilly terrain. In order to resist the slope failure, several stabilisation measures such as implementation of surface and subsurface drainage system, soil grouting as well as buttressing the toe of the slopes w can be effective to certain extent. Since the results are indicating the mode of failure to be toe failure, proper attention should be given at the base of the slopes to prevent the landslides. Being in one of the north eastern states, the slopes are severely affected by the continuous high intensity rainfall in the monsoon season. Hence, keeping in view of this scenario, properly maintained drainage system should be ensured before exposing these hill-cut slopes. Apart from that, re-excavation of the slopes to make them flatter and encouraging vegetation growth can be the last option to get over the disaster.

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