Determination of Geotechnical Properties of Soil and Disaster Vulnerability Analysis

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Abstract—This research aims to understand the factors and processes contributing to landslides by determining the geotechnical properties of soils and conducting numerical analyses of slope failures along the state highway in the eastern part of Mizoram, where Melbuk village is situated uphill of the study sites. This study employed geotechnical approaches and numerical analyses to determine the factor of safety. Due to toe-cutting for the construction and widening of the road, landslides triggered by rainfall occurred. Two landslides, at location 1 and location 2, were investigated where slope failure occurred down slope of Melbuk village. The stability of the slopes and probable landslide mechanisms were determined using various techniques, including limit equilibrium techniques, which evaluate the driving and resisting force equilibrium along possible failure surfaces. The Limit Equilibrium Method is extensively used in geotechnical engineering to assess slope stability and suggest remedial measures. From the Atterberg limit of the soil, it is observed that location 1 soil has silty-clay soil and location 2 has silt soil. The laboratory analysis of soil obtained by direct shear test concluded that the cohesion and angle of friction for location 1 is greater than location 2, indicating that location 1 has higher stability. The stability of the slopes was analyzed, and the factor of safety obtained by different methods is 0.827 and 0.719, respectively. Both the study sites has factor of safety less than 1, indicating an unstable slopes which are highly vulnerable to sliding. A debris slide is observed at both study sites. Hence, remedial measures are suggested based on the research findings.

Keywords: Slope stability, Limit Equilibrium Method, Atterberg Limit, Plastic Limit, Liquid Limit

INTRODUCTION

A landslide is the rapid movement of the earth's material down a slope, which may be composed of soil, rock, vegetation, or debris, or a combination of all, under the influence of gravity with triggering factors that can be natural, anthropogenic, or both (Cruden and Vernes, 1996; Nemcok *et al.*, 1972; Vernes, 1954; Geertsema *et al.*, 2009; Anbalagan *et al.* 2015; Turner, 2018). A stable slope is a condition where all the slope-forming materials remain unchanged and exhibit no displacement (Varnes,1978; Choubey, 1992). If the shear strength of the soil is adequate to counteract this tendency, the hill slope remains stable; otherwise, a slide occurs (Tiwari and Ajmera, 2023).The rate of movement of different landslide types is highly variable. Slides move relatively slowly in comparison to flows (Cruden and Varnes, 1996). The rate of movement during slope failure depends on the nature of the slope-forming material and the shape of the slip surface (Evans *et al.*,2006; Gajamer and Kumar, 2023; Asthana and Sah, 2007;). When ground stress exceeds the strain at which peak ground strength occurs, significant acceleration of movement may happen on slopes made of brittle materials (Nichol *et al.*, 2011). Other materials, particularly sensitive or fast clays,

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lose almost all of their strength when remoulded, leading to extraordinarily fast movement rates.

The risk of a landslide is calculated using landslide risk analysis, considering the risk to people, communities, assets, or the environment (Guillard-Gonçalves *et al.*,2016). Both the magnitude and speed of landslides can vary, occurring either slowly and gradually or quickly and catastrophically (Alcana-Ayala, 2023; Clague 2013). There are several possible causes of landslides, including prolonged periods of intense rainfall, seismic activity, volcanic eruptions, construction or deforestation, and natural phenomena such as soil erosion or unstable slopes (Turner, 2018). Landslides not only represent a major risk to human life and safety but can also seriously harm houses, infrastructures, and the environment (Turner, 2018). Reducing the effects of landslides on communities and ecosystems requires the use of prevention and mitigation techniques, including appropriate land use planning, slope stabilization techniques, and early warning systems (Turner, 2018).

Landslides are investigated and evaluated in geotechnical engineering using various methodologies to comprehend their causes, forecast their occurrences, and lessen their effects (Coutinho *et al.*, 2019; Lasker and Pal, 2012; Safari *et al.*, 2019). Determining possible landslide-prone zones requires an understanding of the geology and geomorphology (Sanei *et al.*, 2015; Bland and Rolls, 2016; Huat *et al.*, 2012). To ascertain the vulnerability and risk of landslides, geologists examine geological structures, rock types, slope aspects, and landforms. Geotechnical parameters, including the Atterberg limit, shear strength, permeability, and compaction, help identify the engineering characteristics of soil and rock (Sanei *et al.*, 2015; Abbas *et al.*, 2017).

Mizoram and the other states of northeastern India are characterized by rough, mountainous terrain with young topography (Nandy *et al.*, 1983). The collision between Indian and Burmese plates formed an intercalated succession of argillaceous and arenaceous deposits, characterized by a Cenozoic sedimentary succession. Predominant rocks originating from the Tertiary period include sandstone and shales, which are representative of ancient shallow marine settings (Nandy *et al.*, 1983). Most of the rock formations trend north-south due to tectonic plate collisions, with the older Barail group rocks found in the eastern portion of the state. The Barail group of rocks is distinguished by discrete siltstone and silty-shale disseminated across very-fine to fine-grained sandstone (Alam, 1991).The entire sedimentary columns of Mizoram consists of an alternating sequence of argillaceous and arenaceous rocks, comprising sandstone, silty-sandstone, mudstone, shale, shaly-sandstone, silty-shale, and their admixture in various proportions(Karunakaran, 1974;Ganju, 1975; Tiwari, 2014). Additionally, there are occasional intra-formational conglomeratic bands and pockets of shell limestone.

Landslides are prevalent, destroying properties, causing loss of life, and economic disruption, particularly in settlement areas and along roads and highways (Mc Coll, 2022). The majority of landslides in Mizoram are triggered by rainfall and human activities (Dinpuia, 2019).The design of a stable slope angle, where deep cuts are involved, is rarely based on stability analysis (Dinpuia, 2019; Kumar *et al.*, 2022). A lack of awareness about the characteristics of the slope, the materials that comprise the hill, and other pertinent elements is the primary cause of most landslide hazards (Alcantara-Ayala and Sassa, 2023). However, with proper planning, these issues can be mitigated, and appropriate precautions can be taken as needed to maintain slope stability (Alcantara *et al.*, 2023; Rovins *et al.*, 2015). The stability of the slopes, and the risk, and vulnerability of landslides are examined using various techniques, including the limit equilibrium method, which evaluates the equilibrium of driving and resisting forces along possible failure surfaces (Duncan, 1996; Dinpuia, 2019).

Anthropogenic activities, including road construction, habitation, and other slope-management-related activities, are the main causes of landslides in mountainous regions. Studying the properties of the soil and rock mass is crucial (Misbahudin, 2020). A scientific study of the geotechnical properties of soil helps us understand the nature of topography and can lead to solid suggestions for mitigating and preventing potential hazards.

The study area (Figure 1) is in the north-eastern part of Mizoram, near the Indo- Myanmar border. The state highway from Champhai town to Zokhawthar village is an important route near the Indo-Myanmar border andserves as a hub for trade and commerce. Various commodities are traded in its lively marketplaces, which are well-known.

Zokhawthar village benefits from its proximity to Champhai town due to its location near the international border with Myanmar. Its significance lies in facilitating trade, offering necessities, promoting cross-cultural interaction, and acting as a transportation centre, all of which support the socio-economic growth and general well-being of the neighbouring districts.

Champhai to Zokhawthar highway has been upgraded from a single-lane state highway standard to a two-lane national highway standard. Following its completion in August

2021, heavy rainfall triggered multiple landslides along the route, rendered it inaccessible in November 2021. This route passes through several villages, including Melbuk. The settlement of Melbuk village is on the upslope of the road, which is 11 kilometers from Champhai town, and is home to 292 families.

Two landslides located at location 1 (23°23'34.00"N; 93°22'42.00"E) and location 2 (23°23'43.00"N; 93°23'18.00"E) have been observed at the toe of Melbuk village along Zokhawthar road. These massive landslides have affected the village community, making five residential houses and one church vulnerable to collapse. The landslides are active rotational slips, causing damage to the newly constructed highway by heavy load exerted by the upslope debris. It has been observed that location 1 has subsided by 6 feet. For this reason, understanding the risks associated with landslides is crucial for safety, risk mitigation, and the security of life. To lessen the environmental impact, the communities can regulate land usage more effectively and implement conservation measures.

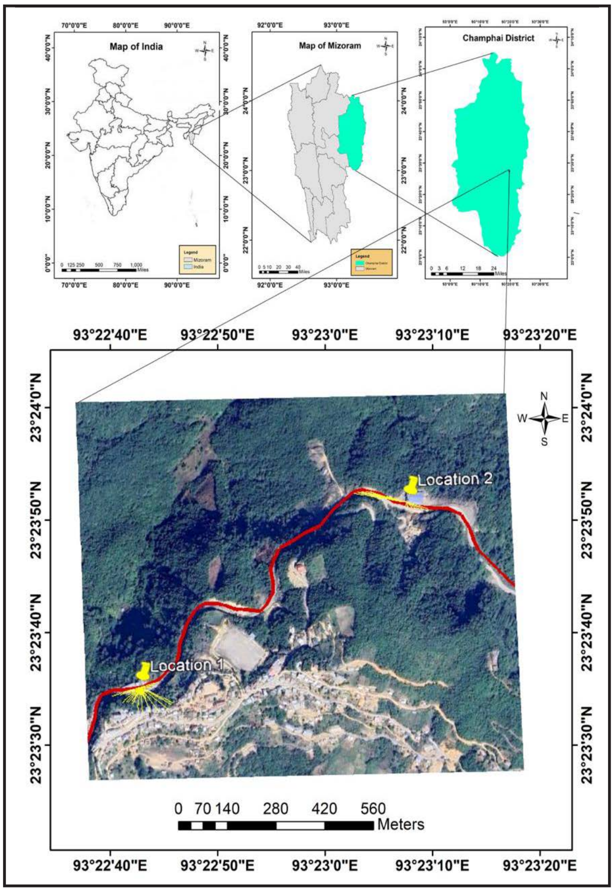

Fig. 1: Location Map of Study Area

MATERIALS AND METHODS

Field Investigations

Field investigations were carried out in the study area to identify probable slope instability variables, such as topography, geology, vegetation, drainage patterns, and landslide evidence, by conducting thorough visual investigations of the sites. Soil samples were collected from the field and tested in the laboratory, where the Atterberg limits and direct shear of the soil were determined (Atterberg, 1911). Detail flowchart depicting methodology is shown in figure 2.

Atterberg Limit

The Atterberg limit is a basic measure of the critical water content levels under different external forces. Liquid limit (LL), plastic limit (PL), and shrinkage limit (SL) are the three primary parameters (Atterberg, 1911). Using the Casagrande apparatus, the liquid limit of the fine-grained soil is determined. The soil sample is combined with water to form slurry. The liquid limit is the moisture content at which the soil transitions from a semi-solid to a liquid state (Casagrande, 1948).

Plastic limit (PL) is the moisture content of soil upon rolling on a flat glass plate until it crumbles (Atterberg, 1911; Casagrande, 1948). Water is added to the soil gradually until it achieves the plastic condition (Atterberg, 1911; Casagrande, 1948). The plastic limit is the water content at which the soil may be spun into a 3.2 mm diameter thread without collapsing.

Plasticity index is used in geotechnical engineering to evaluate the plasticity of fine-grained soils, such as clay or silt(Casagrande, 1932; Roy and Bhalla, 2017). It is an essential parameter for understanding the behaviour of soils. It is obtained by subtracting the value of liquid limit to plastic limit of soil. The greater plasticity in the soil is indicated by higher plasticity index, which suggest that variations in moisture content will result in the soil varying in volume and consistency more significantly (Atterberg, 1911; Casagrande,1932 &1948). Soil with high plasticity index is highly compressible; a high value of the plasticity index indicates a high degree of cohesiveness. High plasticity index soils are typically clay-dominated, whereas low plasticity index soils are typically silt-dominated.

Direct Shear Test

The direct shear test is a common laboratory experiment performed to determine the shear strength parameters of soil (Karsten *et al.*, 2006; Sanei *et al.*, 2015). It is particularly usedto assess the behaviour of cohesive soils like clays and silts. To assess the shear strength of the soil, a controlled shear force is applied to a sample of soil.

Limit Equilibrium Method (LEM)

The Limit Equilibrium Method (LEM) is a method that is extensively used in geotechnical engineering to assess slope stability and its remedial approach (Duncan, 1996). The basic principle is the idea of maintaining the balance between the internal resistive forces supplied by the soil or rock mass and the external forces operating on a slope or structure. The equilibrium conditions are imposed at critical points along the possible failure surfaces because the limit equilibrium technique holds that the structure has the potential to fail. To maintain stability, this usually entails analysing forces and moments in both the vertical and horizontal orientations. An essential parameter in slope stability analysis is the factor of safety, which is the ratio of driving forces to resisting forces. A stable slope is indicated by a factor of safety more than 1, and possible instability is indicated by a factor of safety less than 1 (Duncan, 1996).

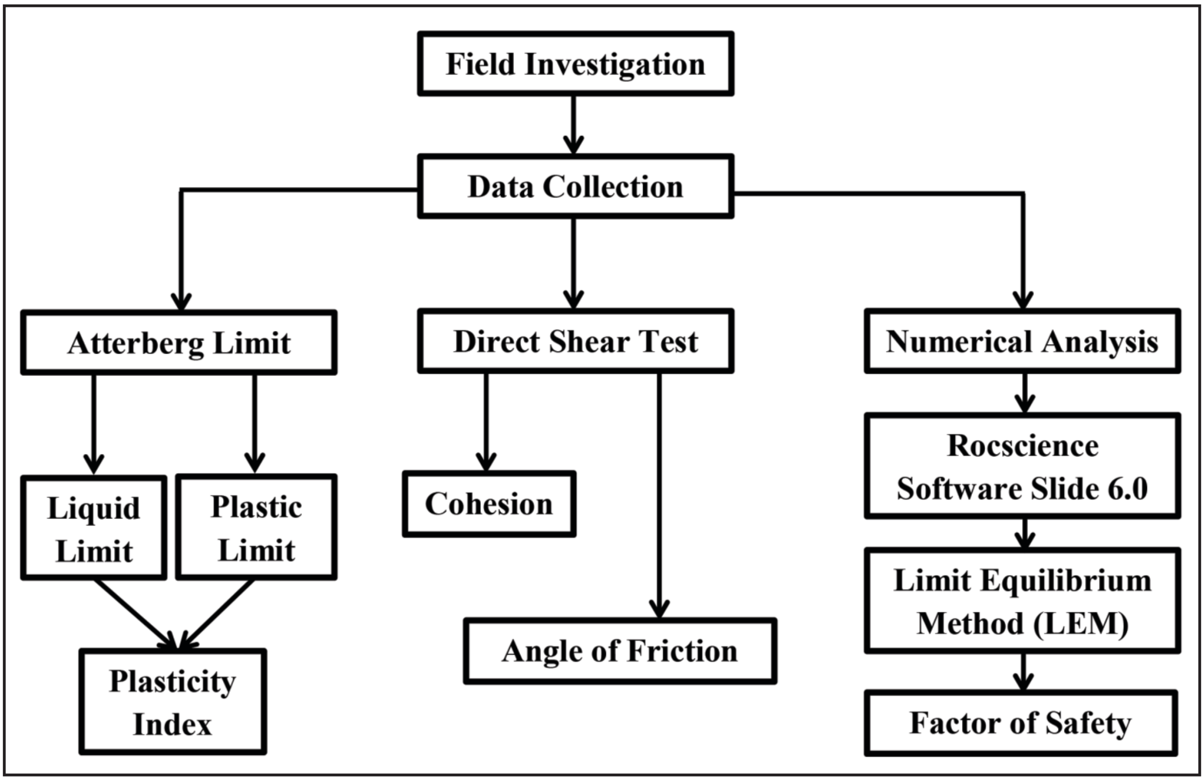

Fig. 2: Flowchart Depicting Methodology

RESULTS AND DISCUSSION

Field photographs (figure3) depict visual documentation of the study sites, where soil samples, geometry, and geology of the field were observed. The coordinates of the study sites were positioned using a differential global positioning system (DGPS).

Determination of Atterberg Limit

Atterberg limits are used to categorize and describe the behaviour of fine-grained soils according to the changes in moisture content that cause the soils to become liquid, plastic, or semi-solid. The Atterberg limit was performed on fine-grained soil, as per Indian Standard IS: 2720 (Part 5)-1985, in order to determine the critical water content. The detailed laboratory observation is given in table 1. The plasticity index of the soil is obtained by the numerical difference between the liquid limit and the plastic limit, where these three parameters, i.e., liquid limit, plastic limit and plasticity index constitute the Atterberg limit. It is used to assess and classify the plasticity and behaviour of fine-grained soils for various construction and soil-related applications.

Fig. 3: Field Photographs: (a) Location 1, (b) Location 2

Liquid Limit

The liquid limit is the minimum water concentration at which soil begins to behave like a liquid. For determining the liquid limit, a 200-gram sample of oven-dried soil that passes through a 425 µm sieve is obtained. The liquid limit test is conducted using the Casagrande method, and the results are recorded based on the number of required blows for the soil to close a groove of a specific length (Casagrane, 1948). The liquid limits for location 1 and location 2 are 20.32 and 20.29respectively. Therefore, the soil of location 2 tends to lose its strength and fail more rapidly at low water content than the soil of location 1.

Plastic Limit

The plastic limit is the water concentration of fine-grained soil below which it loses its plastic properties. As per IS: 2720 (Part 5)-1985, the plastic limit test is performed. The soil is rolled into thin threads around 3 mm in diameter, and begins to crumble. The plastic limit of the soil test was done for 4 trials. The plastic limits for location 1 and location 2 are 19.66 and 17.62 respectively. Since, soil lose its cohesion below their plastic limit, the soil in location 1 has more ability to remain cohesive than location 2.

Plasticity Index

It is a metric used to a13 the soil type is silt. It shows the variation between the liquid limit (LL) and plastic limit (PL) of the soil. It is calculated by obtaining the difference between the liquid limit and the plastic limit (ASTM, 2010). The plastic limits for location 1 and location 2 are 9.54 and 2.67 respectively. Since, soil with a higher plasticity index has a greater potential for changing its volume, therefore, the soil of location 1 possess more ability to change its volume. Based on the plasticity index, location 1 is classified as medium plastic and has a silty-clay soil. Location 2 is classified as slightly plastic and the soil type is silt.

Table 1: Atterberg Limit Values of location 1 and Location 2

Parameters	Location 1	Location 2
Liquid Limit	20.32	20.29
Plastic Limit	19.66	17.62
Plasticity Index	9.54	2.67
Type of Soil	Silty-Clay	Silt

Direct shear test

As per IS: 2720 – 13(1986), this test is used for determining the shear strength of the soil samples. As shown in table 2, the angle of friction obtained for location 1and location 2are 21.29°and 17.84° respectively. Therefore, with a higher angle of friction in location 1, it possesses greater resistance to shear deformation under applied stress. The normal stress versus shear stress of direct shear test is shown in figure 4 and 5.

The cohesion obtained (table 2) for location 1 and location 2 is 26.4 kN/m2 and 14.22 kN/m2 respectively. Since, a higher cohesion of soil implies stronger internal bonding forces between particles, it increases resistance to shear stress and stability. Therefore, location 1 has higher stability and resistance to shear stress.

Limit Equilibrium Method (LEM)

Melbuk Village lies uphill of study sites and the route that connects it to Zokhawthar passes through the downhill of the village. The two locations were analysed using Rocscience software LEM 6.0 (figure 6 and figure 7), and the factor of safety for the two locations wasdetermined. Based on the parameters obtained from the direct sheartest; i.e., cohesion and angle of friction, the slope stability wasanalysed for location 1 and location 2 (table 3).The community has been impacted by these landslides, placing one church and five residential homes at risk of collapsing. It has been observed that location 1 has sunk to a depth of six feet (Figure 6).

Location 1 is an active debris slide caused by large-scale cut slope failure at the toe, comprising a reasonably thick overburden, mostly loose debris. The unchannelized water of domestic waste that penetrated the dense overburden decreased the cohesion of the soil. At the base of the landslide, gabion walls were built without the use of slope-easing techniques. A rotational sliding caused the asphalt to bubble up, causing damage to the road and some of the gabion walls. The impacted region measured roughly 62.2 meters in length and 100 meters in width. The average factor of safety of location 1 for different methods is 0.827.

Location 2 is also an active debris slide due to cut-slope failure at the toe, where unconsolidated earth material moves rapidly down the slope. These cut slope were for the construction of state highway connecting Champhai to Zokhawthar village. A gabion walls at the toe were damaged by landslide debris. The unchannelized widespread flow of water including surface runoff and those penetrating the ground contributes as one of the triggering factors for location 2 slope failure. The sliding area stretched about 189 meters in width and 69.57 meters in length. The average factor of safety for different methods is 0.719.

Table 2: Shear Strength Parameters

Location	Sl. No.	Normal Stress σ (kg/cm^2)	Shear Stress at failure τ (kg/cm^2)	Cohesion (c) (kN/m^2)	Angle of Internal Friction (Φ)
1	**1.**	0.5	0.686	26.4	21.29°
	2.	1	1.151		
	3.	1.5	1.538		
2	**1.**	0.5	0.293	14.22	17.84°
	2.	1	0.495		
	3.	1.5	0.615		

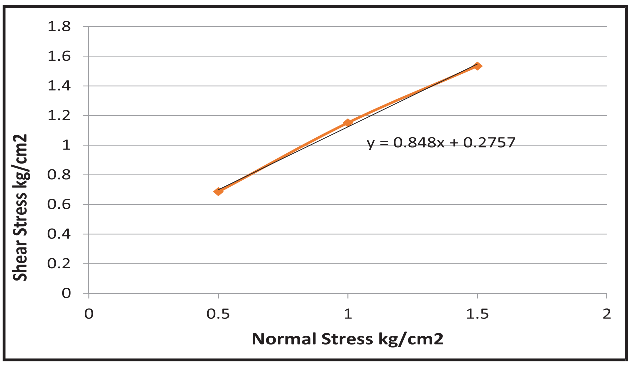

Fig. 4: Normal Stress *Vs.* Shear Stress for Location 1

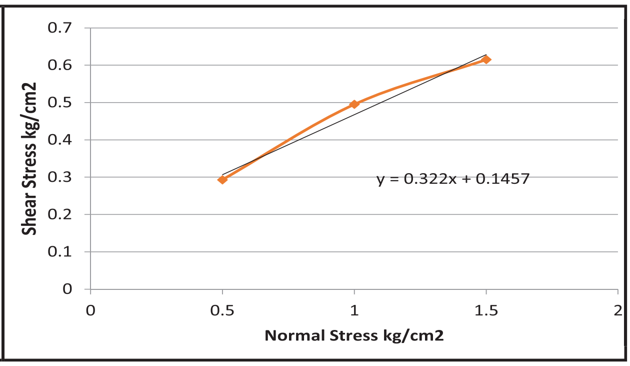

Fig. 5: Normal Stress *Vs.* Shear Stress for Location 2

Fig. 6: Subsidence of Slope and Upward Movement at the Highway

The slope stability analysis using the Limit Equilibrium Method based on the Mohr-Coulomb criterion indicates that the factor of safety obtained through various methods for study sites location 1 and location 2 are less than 1, respectively. It can be understood that the forces exerted by gravity and pore water pressure, which tend to cause slope failure, are greater than the resisting forces of the rock and soil. The stress is below the permissible limit, and slope failure is very likely to occur. Consequently, the slope is vulnerable to failure under saturated conditions.

Table 3: Factor of Safety Analysed by LEM

Method	Location 1	Location 2
GLE/ Morgenstern-Price	0.849	0.74
Janbu Simplified	0.797	0.691
Ordinary/ Fellenius	0.807	0.7
Bishop Simplified	0.857	0.745

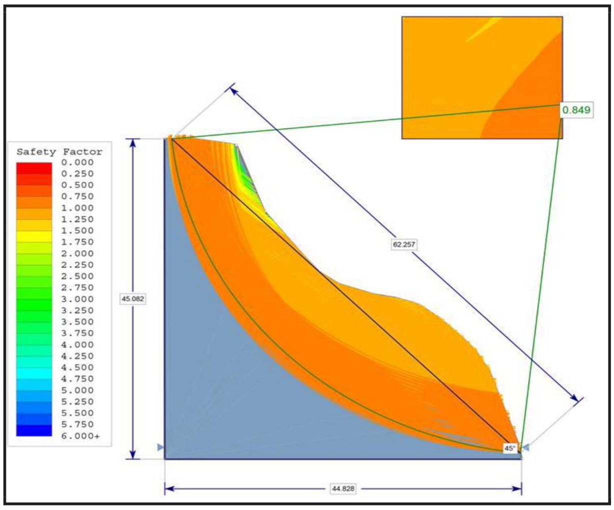

Fig. 7: Slope Stability Analysis using Limit Equilibrium Method for Location 1

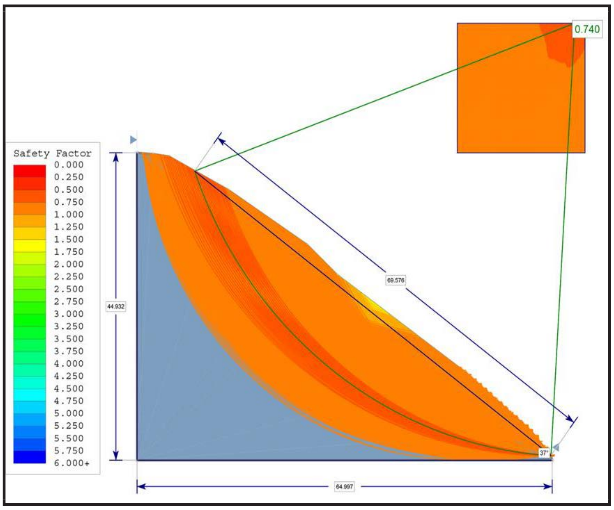

Fig. 8: Slope Stability Analysis using Limit Equilibrium Method for Location 2

CONCLUSION

In this study, the slope stability of the two locations was analysed using Rocscience Software Slide 6.0. From the laboratory analysis, the Atterberg limits concluded that the soil type for location 1 and location 2 is silty-clay and silt, respectively. From the liquid limit and plastic limit, the plasticity index was calculated, with 9.54 for location 1 and 2.67 for location 2. The direct shear test concluded that the soil in location 1 has higher values of cohesion and angle of friction, indicating that the soil possesses more shear strength and stability. The high-angle slopes comprise poor rock mass covered by loose, thick soil, requiring mitigation measures to stabilize the area. The active rotational sliding made the upslope highly vulnerable. Therefore, during the monsoon, excess runoff and percolation may reduce the cohesiveness of the soil, increasing pore pressures and lessening the resisting force, which can act as a triggering factor for slope failure.

Based on the investigations and findings, mitigation strategies are recommended to lessen the risk of hazards and enhance slope stability while also minimizing susceptibility. The generalized measures for slope stability include modifying the high-angle slope by adding a reinforced terrace (benches ≤ 3 m) that slopes from the crown, which can lessen the driving force of the slopes. The kinetic and translational energies of soil will decrease if the slope angle is changed to a milder one.

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