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LEM based analysis of Guthitar landslide along Dharan-Dhankuta Highway

Puskar Raj Gautam [a], Bhim Kumar Dahal [b]

[a,b] *Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[a] puskar.gautam619@gmail.com , [b] bhimd@pcampus.edu.np ,

Abstract
Dynamic slope instabilities pose significant challenges to infrastructure integrity and safety, particularly in mountainous regions. This study investigates the phenomenon of moving landslides along the Guthitar section of the Dharan-Dhankuta Highway, where persistent road settlement issues have been observed for a very long period of time. Employing Limit Equilibrium Method (LEM) analysis through SLOPE/W software, we assesed the weak slope stability contributing to these occurrences. The analysis reveals a factor of safety of about 0.9 in the slope model, indicative of such precarious conditions. The instabilities and road settlement problems observed on site have been sufficiently replicated in our soil model. The findings underscore the importance of understanding the causes and mechanisms of slope failure problems before implementing effective mitigation strategies to safeguard critical infrastructure and mitigate hazards in landslide-prone regions.

Keywords
LEM, GeoStudio, Slope Stability

1. Introduction

1.1 Background

A huge part of Nepal lies in the mountainous region. The main mode of transportation in these parts is roadways. So, the roads passing through hill slopes, which are major zones where soil and rocks are weathered and eroded, is an inevitability. When mountain roads pass through already weak and problematic hill slopes, slope movement can occur. The phenomena might be complex and multi-faceted but its mechanism and triggers must be identified and analyzed in order to predict and prevent the loss of lives and infrastructures. The primary force that continuously pulls materials downslope is gravity. The structural integrity of rocks and soil is weakened by weathering and erosion, which makes them more prone to failure. The most important factors that facilitate this phenomenon are the nature of the soil layers into depth, the slope configuration and geometry and the groundwater conditions[1]. A landslide may begin with very small movement, but with gradual acceleration it can end with large displacement producing serious damages[2].

Slope instability is made worse by the unchecked growth of road networks, particularly in the wet season. It is worth noting that the likelihood of landslides occurring within 100 meters of a road due to rainfall is more than twice that of landslides induced by earthquakes. In Nepal, developing rural areas requires the construction of roads. Unfortunately, landslides and erosion are a problem associated with Nepal's poorly constructed mountain roads, affecting people's lives and means of livelihood[3]. A number of case studies have provided evidence about the ways in which changes in land cover, land use, and the resulting modifications impact soil erosion in various temporal and spatial dimensions [4]. Additionally, regions with extremely vulnerable soil to erosion have a higher risk of landslides [5] and [6].

This study is done to utilize the limit equilibrium method (LEM) analysis as a tool to generate the slope model of the landslide. This will aid in assessing the continuous road settlement and local landslide failure problems. Only after evaluating the cause and mechanism of movement can an educated opinion be provided for the recommendation of possible mitigation measures. Hence, this study will also contribute in understanding the dynamic processes of road side slope failure that is persistent in many hill roads of Nepal.

1.2 Study area

The troublesome land movement site at Guthitar of Dhankuta district lies about 10 km south of Dhankuta Bajaar. The study area is situated between latitudes 26°57'42"N and 26°57'17"N and longitudes 87°19'15"E and 87°19'35"E as seen in Figure 1.

The study area is in a forest area with medium dense vegetation with the road passing through the middle of the section. The area is affected by continuous movement causing significant subsidence of the highway since its inception in 1987 and recent activation of old landslides on the slope. The mass movement system was mapped by Brundsen et. al. in his geomorphological survey shown in Figure 2. [7]

Continuous maintenance of the road is required to keep the road functioning. Since small continuous movement of the slope can contribute to a large and catastrophic failure, the underlying problem and mechanism must be acknowledged. Continuous slope monitoring is needed to understand the complex mechanism behind the problem. Various slope problems like settlement of old road, local landslides at bottom of the slope and side cutting by natural streams on either sides of the slope can be seen in aerial photograph of the area as seen in Figure 3

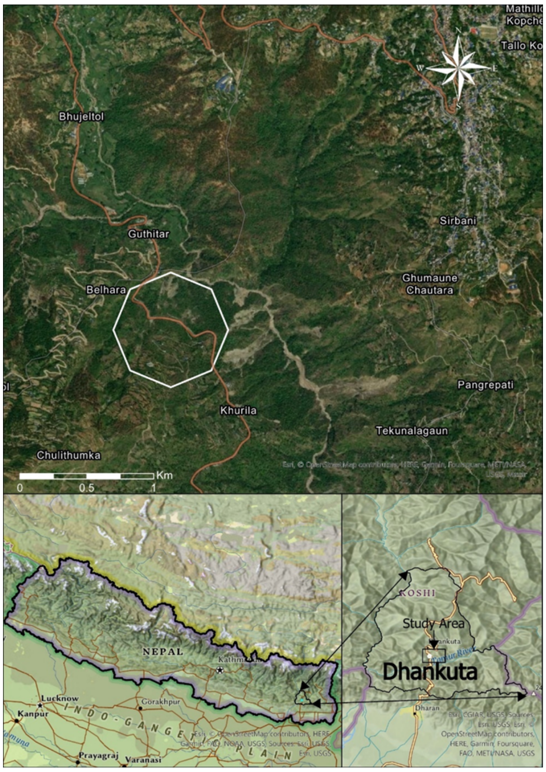

Figure 1: Location of the study area

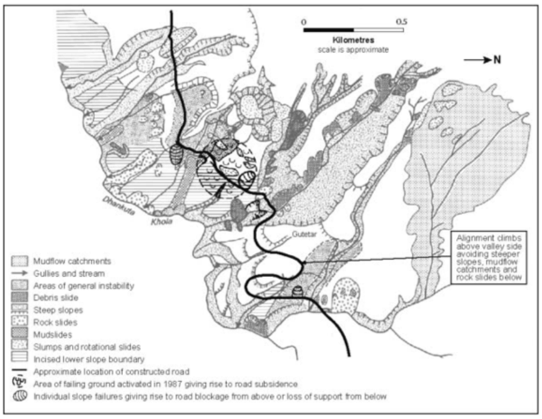

Figure 2: Mass movement system mapped in the geomorphological survey by Brundsen in 1981 [7]

Figure 3: Settlement of road level and activation of local landslides at the bottom part of the slope

2. Material and Method

2.1 Slope Stability Analysis

Slopes can be either man-made or occurring naturally. There are forces at play that cause soil to shift from higher elevations to lower ones. Slopes inherently seek stability, and any inclination towards movement can be termed as instability. If a slope experiences actual movement, it results in slope failure. Slope instability has consistently posed a significant challenge in Nepal, leading to substantial human casualties and property damage. To properly manage these hazards, slopes must be thoroughly assessed before, during, and after the construction of any infrastructure. The 21st century has added to advancements of man-made structures such as earth dams, railroad embankments, hydraulically produced dams, and roads, in addition to geotechnical engineering marvels.

The factor of safety of both artificial and natural slopes can be assessed using different techniques including limit equilibrium, discrete element methods, finite element methods, finite difference approaches, soft computing, etc. A popular method is the limit equilibrium method, which predicts the slope's stability using a single factor of safety value. Finite element approaches were later developed by a number of scholars as a powerful means of obtaining answers to slope stability problems. However, the problem of slope stability is linked to both risk and reliability. So, depending just on one aspect of safety will not be sufficient for the implementation of safety measures against slope failure. The probabilistic analysis-derived reliability index is needed to examine the slope's dependability. [8]. The selection of the analysis method will rely on factors such as the problem's characteristics, the available quality and type of input data, the desired analysis outcomes, and the researcher's level of expertise and preferences.

2.2 Limit Equilibrium Method

One of the earliest methods developed to examine the stability of a slope is the Limit Equilibrium Method, or LEM. Mobilized strength and applied stress in the test slide surface of slope are calculated. Here, the safety factor is determined using these two supplied quantities. The least and most critical value for each trial failure surface is determined. The assumptions made about the sliding surface's geometry offer the primary distinction among the many techniques of achieving limit equilibrium, including logarithmic, planar, and circular methods. While moment or force equilibrium, or sometimes both, rely on similar assumptions as the equilibrium equation, there are instances where the consideration of the third dimension, perpendicular to the cross-sectional plane, influences the slope's behavior [9]. In analyzing slope stability, slice methods are commonly employed within limit equilibrium approaches. There are several LEMs, with some of the main ones listed are: The Ordinary Method of Slices, Bishop's Methods, Modified Bishop Methods, Janbu's Method, Morgenstern- Price Method, Spencer's Method, Corps Of Engineers Method, Sharma Method, Lowe-Karafiath Method.

2.3 GeoStudio with SLOPE/W

GeoStudio with SLOPE/W, developed by GEO-SLOPE international Canada, is a software for analyzing the stability of structures based on the principle of limit equilibrium principle. It covers a variety of methods like the Corps of Engineers', Ordinary Method of Slice (OS), Bishop's (BS), Janbu Simplified (JS), Spencer's (SP), Morgenstern-Price (M-P), and Sharma approaches. Morgenstern-Price (M-P) approaches is the only one utilized for FOS computations in the current investigation. Both numerical and visual representations of the slope/W results are available. SLOPE/W analysis's primary benefit is that it enables handling of every possible slide in a single model with an appropriate safety factor.

2.3.1 Procedure of slope modeling in SLOPE/W

Geometrical modeling (2-D) representation of selected slope through site observation and topographic assessment are the primary processes used for slope stability analysis utilizing SLOPE/W software. The factor of safety was calculated by SLOPE/W based on the principles of limit equilibrium. Multiple slip surfaces were examined in order to estimate the minimum factor of safety. The definition of a slip surface includes variables like entry and exit points, radius and grid, fully specified, auto search, etc. The software's auto search feature was utilized to find the critical slip surface and related safety factor. A tabular and graphical representation of the relative interpretation of FOS for the critical slope segment under various predicted scenarios was prepared. Based on the lowest factor of safety less than the acceptable limit, critical cases were identified.

3. Methodology

3.1 Slope Geometry

The cross section of the slope deemed weakest was used as the geometry of the slope for its stability analysis.The contour map obtained from the topographic survey was used as the basis of the slope geometry and was cross-checked with the section obtained from Google Earth Pro. The slope geometry used for stability analysis starts from the local river at the base (Dhankuta Khola) at an elevation of 530m and stretches up to the top of the landslide zone at an elevation of 800m.

3.2 Slope Strata and soil properties

For the stratification of the slope geometry, the information available obtained from the borehole data was used. Change in the corrected SPT-N values were taken as change in soil stratum and the type of soil layer was also interpreted from the corrected SPT-N values. The soil geometry and strata used in the analysis is shown in Figure 4. The soil properties of such strata were obtained from lab tests of the sample obtained during the boring process. The material properties of the soil used in the slope model is shown in Figure 5.

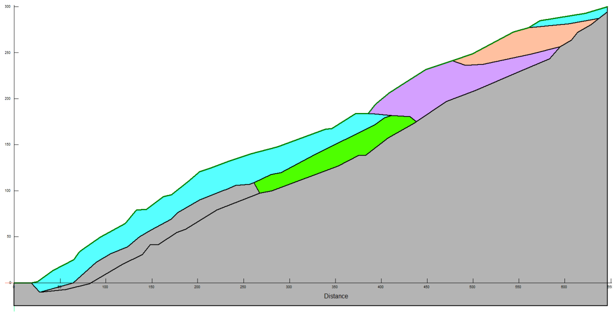

Figure 4: Soil geometry and strata used in the analysis

Soil Type	Material Model	Unit Wt (kN/m3)	Shear Strength Parameters	
			Cohesion (kPa)	Friction Angle (Φ)
Dry Colluvium Debris	Mohr-Coulomb	17.5	2	35
Highly Fractured and Dry Rock Mass	Mohr-Coulomb	17.5	2	33
Saturated Soil	Mohr-Coulomb	17.5	2	30
Strong Rock Layer	Mohr-Coulomb	17.5	10	40
Bedrock	Bedrock / Inpenetrable			

Figure 5: Soil parameters used in the analysis

3.3 Model Analysis

The analysis type was selected as Morgenstein-Price method, the mesh was generated ensuring proper discretization. The entry and exit slip surface points were introduced in the model for calculation of factor of safety. The factor of safety represents the ratio of resisting forces to driving forces for slope stability. SLOPE/W analyses all possible slip surface under the given condition of exit and entry boundaries and displays the weakest one.

4. Results and Discussions

4.1 Results of slope model

The weakest failure surfaces achieved at the top portion, road level and bottom portion of the slope are described below:

4.1.1 Top portion of the slope

Upon analysis it was evident that the top portion was almost stable and the lowest Factor of Safety observed during the analysis was 1.364 after testing with different slip surface. The slip surface with its FoS is shown in Figure 6. Slope Monitoring from the inclinometer casing installed in Borehole 1 showed a small movement over time in with the failure plane lying below the 26m depth of installed casing. LEM analysis suggests otherwise as all the possible slip surfaces passing through the borehole site are observed to be fairly stable with the minimum factor of safety being 1.364.

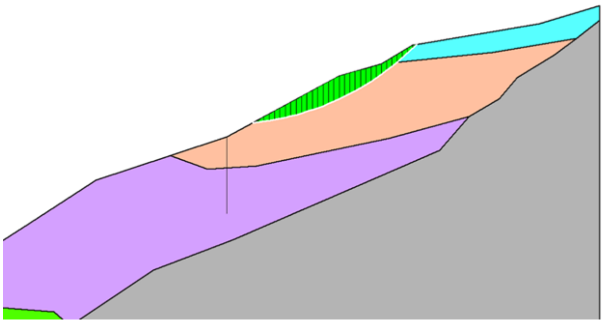

Figure 6: Weakest plane in the top portion of the slope

4.1.2 At road level

As is evident from the field data, localized slope failure is occurring at road section of the slopes. This is supported by the analysis as analysis for local slope with different probable slip surface showed failure as the FoS was 0.994, 1.030, 1.018 and 0.918. This is one of the critical local zones of the Guthitar slope. The continuous subsidence of road level and the presence of local landslide just above the road section as observed in the field is accurately predicted by this analysis. The slip surfaces along with their Factor of Safety are shown in Figure 7

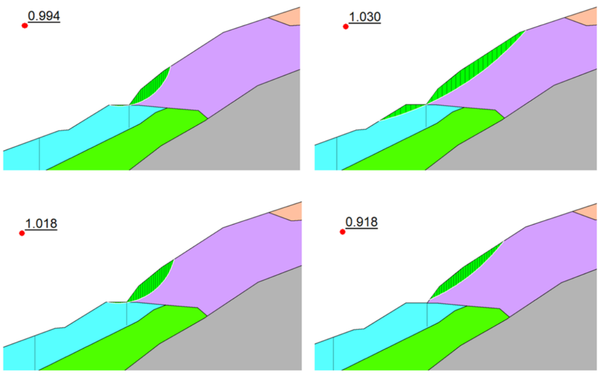

Figure 7: Slip Surfaces near Road section

4.1.3 Below the road section

Another steep slope was below the road section. As done in previous sections, slope stability analysis was performed considering different slip surface possible. The result showed that the slope was unstable. The FoS of the local failures at the area were 0.942, 0.964, 0.950, 1.049. The slip surfaces along with its FoS are shown in Figure 8

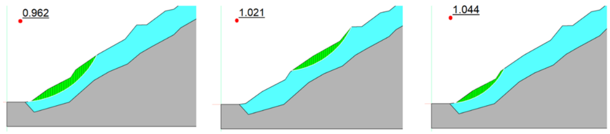

Figure 9: Slip surfaces at the bottom of the slope

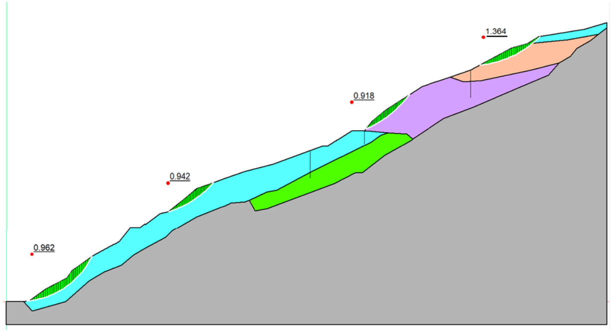

Figure 10: Various Slip Surfaces obtained from LEM Analysis with respective factors of safety

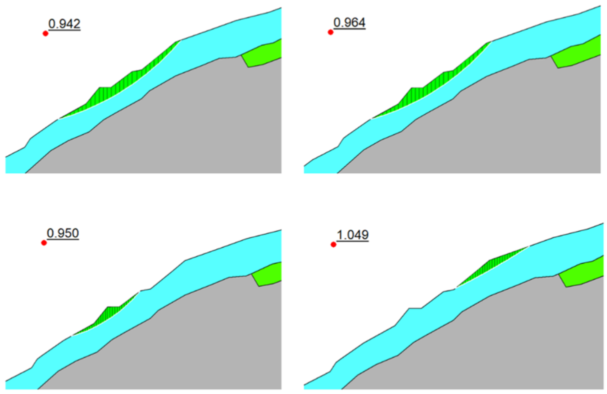

Figure 8: Slip surfaces below road level

4.1.4 Near the Dhankuta Khola at the bottom the slope

Another local slope which is likely to fail is the steep slope at the very bottom of the slope near the Dhankuta Khola. The slope stability analysis was performed considering different possible slip surfaces. The result showed that the slope was nearly unstable as the FoS were all below 1.5. The FoS of the local slope below the lower spring were 0.962, 1.021, 1044. The slip surfaces with these FoS are shown in Figure 9

Figure 10 shown the weakest planes of failures throughout the slope with their respective factor of safety. [H]

4.2 Discussions

Applying limit equilibrium method on various zones of the study area, area of high slope instability have been identified. The roadway settlement and road side slope failure are persistent problems in the site. A factor of safety of 0.918 was observed in this area in our slope model. Various local landslides have recently activated on the bottom parts of the slope along with severe side-cutting by the natural streams lying on either side of the slope. Our slope model also replicates this instability showing a factor of safety of 0.942 and 0.962 in these areas. No such prominent and visible instability can be observed in the top part of the slope above the road section and our slope model gives a reliable safety factor of 1.364 in this area. This shows that the use of LEM based software like SLOPE/W can be useful in determining the slope instability.

5. Conclusion and Recommendations

In conclusion, this study has provided valuable insights into the dynamic slope instabilities affecting the Guthitar area of the Dharan-Dhankuta Highway. It has proved that GeoStudio with SLOPE/W can be a powerful tool in analyzing the failure mechanism of a landslide given that sufficient information about the slope geometry and soil properties is available. Through this comprehensive analysis, the fundamental processes responsible for slope collapse and persistent road settlement in this area have been determined. A factor of safety of roughly 0.9 was found by the Limit Equilibrium Method (LEM) analysis, indicating unstable conditions and a higher risk of moving landslides.

The findings of this study underscore the importance of understanding slope instability in mountainous regions. Only after proper identification of the causes and mechanisms of the failure can landslide management and mitigating measures be recommended. Addressing these challenges requires a multidisciplinary approach that integrates geological, engineering, and environmental considerations. Effective mitigation strategies should be tailored to the specific conditions and vulnerabilities of the study area, incorporating both structural and non-structural measures to enhance resilience and minimize the impacts of slope failure on infrastructure and communities.

As recommendations for future research in this subject, an extensive investigation into the mitigation measures can be done. The slope modeling can be done using more powerful tools like Plaxis2D or others that utilize Finite Element Method (FEM). Investigation of the problem can be done using long-term slope monitoring approach. Hazards and risks associated with the slope failure problem can be identified.

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