"STABILITY ANALYSIS OF A HILL SLOPE IN UZAN BAZAAR GUWAHATI USING FEM AND LEM APPROACH"

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY

IN

CIVIL ENGINEERING
(Geotechnical Engineering)

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CANDIDATE'S DECLARATION

I, **SANDEEP SHARMA**, **2K19/GTE/501**, student of **M.Tech. (Geotechnical Engineering)**, hereby declare that the project dissertation titled **"Stability Analysis of a Hill Slope in Uzan Bazaar Guwahati using FEM and LEM Approach"** is submitted to the Department of Civil Engineering, Delhi Technological University, Delhi, by me in partial fulfilment of requirement for the award of degree of **Master of Technology (Geotechnical Engineering).** This thesis is original work done by me and not obtained from any source without proper citation. This project work has not previously formed the basis for award of any degree, diploma, fellowship or other similar title or recognition.

Place: Delhi **SANDEEP SHARMA**

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CERTIFICATE

I hereby certify that project dissertation titled **"Stability Analysis of a Hill Slope in Uzan Bazaar Guwahati using FEM and LEM Approach"** which is submitted by **Sandeep Sharma, 2K19/GTE/501**, Department of Civil Engineering, Delhi Technological University, Delhi, in partial fulfilment for the award of degree of Master of Technology, is a project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any degree or diploma to this university or elsewhere.

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ABSTRACT

The stability analysis of natural slopes holds significant importance in geotechnical design. Both engineering consultancies and research organizations utilize various computer aided design software to address these slope stability problems. This approach provides the ability to precisely anticipate critical failure surfaces through diverse methodologies.

This M.Tech thesis focuses on performing stability analysis of a natural slope located in Uzan Bazaar Guwahati Assam.

There have been frequent and periodical occurrences of natural disasters in the State of Assam, viz. landslides, earthquake tremors, which not only caused lot of causalities and destruction of property, but also damage roads and infrastructures.

The natural slope lies on left bank of mighty Brahmaputra River. Most of the Kharghulli Hill is covered with dense vegetation and soil cover including semi-consolidated to consolidated nature of slide cum slope debris material which consist of nala borne material second layer from top including highly to completely weathered, weak, jointed and fractured Gneisses/Schist is prone to slope failures.

The Finite Element Method (FEM) based on the Shear Strength Reduction (SSR) technique offers several advantages. It enables the prediction of support elements' failure. The support elements such as micro-piles, ground anchors, geogrids, etc, as well as the calculation of factors of safety. This capability enables comprehensive analysis and assessment of the support elements, contributing to a more accurate understanding of their performance and potential failure modes.

Despite these benefits, SSR has not been widely adopted for routine slope stability analysis, likely due to limited experience with the tool and the scarcity of published information regarding its accuracy.

To tackle this issue, the objective of this thesis is to conduct its performance comparison with the widely employed conventional limit-equilibrium method.

The findings indicate a favourable correlation between both these methods of analysis, establishing a strong level of agreement between the two approaches.

Major Keywords: Finite Element Method (FEM), Limit Equilibrium Method (LEM), Plaxis, Talren, Self-drilling Anchors (SDA), Cable Anchors.

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Chapter-1: INTRODUCTION

1.1. Background and significance of the study

Landslides are natural geological phenomena that can have severe consequences on human settlements and infrastructure. In the hilly terrain of Guwahati, the capital city of Assam in Northeast India, landslides pose a significant hazard and have been a recurring issue. Guwahati is situated in the foothills of the Shillong Plateau and is surrounded by steep slopes, making it susceptible to slope failures and mass movements. The combination of heavy monsoon rains, geologically fragile slopes, and anthropogenic activities further exacerbates the landslide vulnerability in this region.

Guwahati, a city known for its significant rainfall, encounters particularly intense precipitation in monsoons, June to Sept. This substantial rains poses a challenge for the region due to the presence of steep slopes in the surrounding hills. These slopes consist of a combination of rocks and loose soil, which, when subjected to the heavy downpour, become thoroughly saturated.

This saturation weakens the stability of the slopes, making them prone to landslides triggered by factors such as gravity, soil erosion, and seismic activity.

Furthermore, human activities, including deforestation, unregulated construction, and improper land-use practices, have significantly increased the susceptibility of the region to landslides. Deforestation leads to the loss of vegetation cover, which plays a crucial role in stabilizing slopes by absorbing rainfall and binding the soil together. Construction activities, especially on steep slopes, often involve improper engineering practices and inadequate soil stabilization measures, further compromising slope stability.

Given the recurrent nature and severity of landslides in Guwahati, understanding the factors contributing to these events and developing effective mitigation strategies is of paramount importance. This thesis aims to perform stability analysis for one such slope in Uzan Bazaar in Guwahati using FEM and LEM methods, compare both the analysis approach and suggest appropriate preventive measures.

By enhancing our understanding of this natural hazard and implementing appropriate measures, we can minimize the risks associated with landslides, protect lives and infrastructure, and promote sustainable development in this geologically vulnerable region.

1.2. Research Objective

The main aim of this study is to undertake comprehensive slope stability analysis of a natural slope by employing both Finite Element Method (FEM) and the conventional Limit Equilibrium Method (LEM).

The analysis of slope stability entails the examination of various contributing factors that can lead to slope failures, including characteristics of the soil, slope geometry, and external influences such as rainfall and seismic activity.

The Limit Equilibrium Methods rely on the principles of forces and moment equilibrium to determine the stabilizing conditions, whereas the Finite Element Methods utilize stress-strain behaviour to elucidate behaviour of the slope. In this study, the slope analyses were carried out on softwares Bentley's Plaxis 2D for FEM and Terrasol's Talren for LEM.

The outcomes obtained from both the FEM and LEM approaches shall be assessed and compared, facilitating the identification of suitable preventive measures for slope protection. By analysing and evaluating the results, this research aims to propose effective measures to safeguard slopes from potential instability.

This involves assessing the accuracy, efficiency, and practicality of each method in predicting slope stability. By conducting a comparative analysis, the research objective is to provide insights into the strengths and limitations of FEM and LEM for slope stability assessment.

Chapter-2: LITERATURE REVIEW

Slope stability poses a significant and precise challenge in geotechnical engineering.

When the geometry and material properties of slope are already known, conducting slope stability investigations using computer-based methods appears to be a relatively uncomplicated task. Nonetheless, selecting the most suitable investigation method demands careful deliberation, which includes gathering field conditions and failure observations. These observations play a crucial role in comprehending the mechanisms behind slope failures, which consequently dictate the appropriate slope stability analysis method.

At present, the 2D analysis of slope is widely favoured due to their simplicity. Geotechnical calculations frequently rely on software that incorporates both the limit equilibrium method (LEM) and the finite element method (FEM). By employing these computational approaches, we can effectively analyse and appraise any slope stability problem, assist in making informed decisions then recommendations regarding slope stability and reinforcement measures.

2.1. Slope Failures Mechanisms

Different kinds of failures can happen depending on factors such as material properties, groundwater conditions, and slope height and angle. A translational slide is a common failure type that happens along weak zones in coarse-grained soils or jointed bedrock conditions. Instead, rotational type of slide is classic in fine-grained soil.

The rotational type of slide is further classified as a toe slide based on the location of the failure surface.

For a stable slope, the shear strength parameters of the soil essentially exceeds the shear stress requirement for an equilibrium. Slope instability happens when the shear strength is low and unable to resist the shear stresses applied. This can happen due to a decrease in shear strength or an increase in shear stress.

Factors that can lead to a reduction in shear strength include:

- Increased pore water pressure
- Slope cracking

- Disintegration of material
- Creep under continual loads
- Weathering
- Cyclic loading

Conversely, an elevation in shear stress can be attributed to:

- Top loading on the slope
- Water pressure in cracks at the slope's apex
- Increased soil weight caused by higher water content
- Excavation at the slope's base
- Decreased water level at the base of the slope
- Seismic activity

The slope failure usually occurs due to a combination of various factors. In most cases, several causes coexist simultaneously, making it difficult and technically incorrect to attribute the failure to a single primary cause.

2.2. Mohr Coulomb Model

Shear strength refers to the maximum shear stress that soil can endure. It represents the threshold at which soil movement occurs due to significant shearing stresses, leading to the displacement of a large mass of slope or the relative displacement of a slope and its foundation in relation to the surrounding stationary mass. The shear strength is primarily influenced by effective stress, irrespective of whether failure happens under drained or undrained conditions. The Mohr-Coulomb strength envelope provides a graphical representation of the relationship between shear strength and effective stress.

2.3. Limit Equilibrium Analysis

The determination of shear strength along a slip surface is facilitated by employing the Mohr-Coulomb failure criterion within these methods. The limit equilibrium condition arises when the mobilized shear stress constitutes a portion of the shear strength. When failure occurs, the shear strength is entirely mobilized along the critical slip surface. To assess the factor of safety (FOS) against slope failure, the available shear strength is compared to the mobilized shear strength. The available shear strength relies on factors such as soil type and effective normal stress, whereas external forces exerted on the soil mass affect the mobilized shear stress.

In the limit equilibrium (LE) analysis, the sliding mass is divided into distinct slices, and the determination of shear and normal inter-slice forces takes place. The equilibrium conditions are then satisfied by employing suitable force and/or moment equations. The initial LE method for analysing round slip surfaces was introduced by Fellenius in 1936, and later, Bishop developed a revised method specifically for circular slip analysis in 1955. Janbu, in 1954, presented a technique for analysing non-circular failure surfaces by dividing the potential sliding mass into vertical cuts. Subsequent advancements were made by Morgenstern-Price in 1965, Spencer in 1967, Sarma in 1973, and other researchers, with each focusing on different assumptions concerning inter-slice forces.

This study specifically utilizes Bishop's simplified method, which is widely adopted and yields reasonably accurate results for calculating the factor of safety (FOS). Each limit equilibrium (LE) method is built upon specific assumptions concerning inter-slice forces, and the variations primarily arise from the approach employed to determine these forces. Additionally, differences can be observed in the selection of the critical slip surface shape used in FOS calculations.

Bishop's method ensures equilibrium of moments and vertical forces related to the base normal force, while also considering the inter-slice normal forces. It is particularly well-suited for analyzing shear surfaces of circular shape.

A visual depiction of a typical slice within a potential sliding mass demonstrates the various forces exerted on the slice. These forces encompass normal and shear forces acting on its base, left side, and right side.

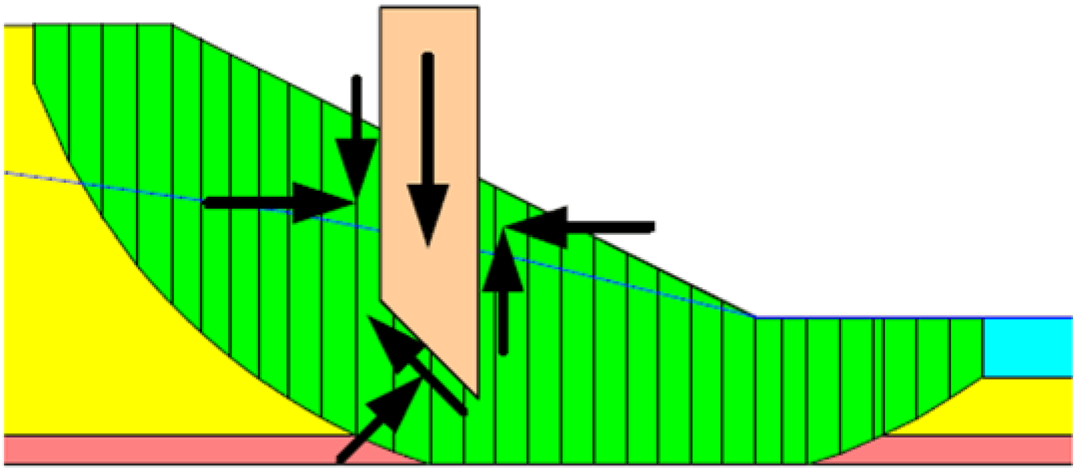

Figure 2-1 A slide divided into individual slices and equivalent forces

2.4. Finite Element Analysis

When conducting analyses, the finite element (FE) and finite difference (FD) methods are widely employed numerical techniques. In this particular study, we specifically concentrate on utilizing the finite element method for our analyses.

The finite element method doesn't make assumptions about the shape and location of the failure slip surface, unlike traditional methods. It allows for more flexibility in analysing slope stability. In traditional methods, FOS is calculated based on a predetermined failure surface. In FEM, there is no requirement to assume forces between adjacent slices of soil, which simplifies the analysis.

FEM divides the slope into smaller elements or pieces called meshing. It calculates stresses as well as strains using the behaviour of the soil. Failure happens certainly in areas where the material shear strength can't withstand the applied shear stresses. The method can monitor progressive type of failure until complete shear failure reaches.

In the finite element method, the factor of safety can be determined by employing the "c-φ reduction", which involves calculating a reduction factor (RF). This procedure gradually decreases the soil strength parameters till failure is reached. By utilizing the shear strength reduction technique, the finite element method is capable of calculating the factor of safety, which is equivalent to the RF value, for slopes.

2.5. Factor of Safety

The assessment of slope stability commonly involves the utilization of a factor of safety (FOS) to determine the adequacy of stability. This FOS is derived by comparing the resisting forces with the driving forces along a potential failure surface. In finite element (FE) analyses, an equivalent measure to the FOS is calculated as the strength reduction factor (SRF).

In limit equilibrium (LE) analyses, it is assumed that the FOS remains constant along the entire slope surface, representing an average value for the assumed slip surface. An ideal FOS of 1 signifies a state of equilibrium between the driving and resisting forces. A higher FOS indicates enhanced stability, whereas a lower FOS suggests instability of the slope.

However, since there are inherent uncertainties in the inputs used to compute the FOS due to various factors, it is crucial to have a larger FOS to ensure the safety of the slope and mitigate the risk of failure.

Chapter-3: STUDY AREA

3.1. Background of the Project

Assam, situated in the north-east part of India, boasts a remarkable array of geographical characteristics. It shares borders with Bhutan and Arunachal Pradesh to the north, Nagaland and Manipur to the east, Meghalaya, Tripura, Mizoram, and Bangladesh to the south, and West Bengal to the west via the Siliguri Corridor. Spanning across area of about 80,000 square kilometres, it accommodates a substantial population.

The landscape of Assam can be categorized into three distinct physiographic divisions:

- Eastern Hills of the Northern Himalayas
- Brahmaputra plain of the Northern Plains
- Karbi Anglong area of the Deccan Plateau

Assam frequently experiences natural disasters such as landslides and earthquakes, resulting in casualties, property damage, and infrastructure destruction. Landslides can be triggered by factors like rainfall, earthquakes, volcanic activity, changes in groundwater, human activities altering the slope, or a combination of these factors. Several forces contribute to slope stability and mass movements in the region, including slope angle, lithology and structure, rainfall, hydrological conditions, vegetation, and seismicity.

Figure 3-1 Landslide at Raj Bhavan, Guwahati Assam

3.2. Location of Project

The project area falls in Kamroop District of Assam and lies on Khargulli Hill of Shillong Platue situated on left bank of mighty Brahmaputra River.

Figure 3-2 State map of Assam

3.3. Physiography

The Kharghuli hill in Guwahati is an extension of the Shillong Plateau, which dates back to the Pre Cambrian Age. It consists of a complex geological formation comprising granite gneiss, biotite schists, gneiss, and quartzite. These formations are overlain by sedimentary layers from the Pleistocene-Holocene period.

From a physiographic standpoint, Guwahati can be categorized into three distinct sections: the southern hilly region, the central area characterized by alluvial plains, and the north-western parts encompassing swamps along the Brahmaputra flood plains. Within the city, there are numerous dissected residual hills, predominantly covered in scrub land, and residential areas with sparse population. The southern portion of Guwahati is encircled by an extension of the Jayantia hills originating from Meghalaya.

In addition to the Brahmaputra River, the Basistha and Bharalu rivers are the main drainage systems within the city. Residual hills make up a significant portion of Guwahati, accounting for approximately 68.49% of the total area, while alluvial plains cover about 31.51%, and water bodies with Paleo channels occupy 7.82% of the area.

3.4. Climate and Rainfall

Guwahati is situated at an elevation of 56 meters above sea level and experiences a sub-tropical humid climate characterized by substantial precipitation, hot summers, and high levels of humidity. The average temperature throughout the year varies between 12 and 38. In winter, temperatures various 15°C to 25°C in day time-period, while night-time temperatures varies 8°C to 15°C. During the summer season, daytime temperatures range from 25°C to 38°C, and night-time temperatures range from 15°C to 25°C.

On an annual basis, the district receives an average rainfall of 1752 mm, with a coefficient of variation measuring 15.3%. As per data provided by the India Meteorological Department (IMD), the normal annual rainfall for the district is recorded as 2125.4 mm, with a total of 96.5 rainy days.

3.5. Geomorphology

Geomorphology helps us understand the distribution of different landforms, deposits on the surface and near the surface, and the processes and time involved in their formation. It provides insights into how the landscape of a region develops.

The city has numerous dissected hills, and weathering and erosion have caused rocks and soil on these hills to break down. During the monsoon season, heavy rainfall increases the risk of landslides in the region. The rocks and soil on the hills are easily eroded through nearby ravines, which act as catchments during the monsoon season.

3.6. Drainage/Drainage Network

The drainage network refers to the natural pattern formed by streams, rivers, and lakes in a specific area, indicating how water flows through the landscape. It plays a crucial role in identifying areas prone to landslides. The drainage network reveals the slope formation and erosion aspects of the region or hill slopes, helping to identify areas with a higher risk of landslides.

Unfortunately, many human settlements have disrupted and encroached upon the natural drainage network by constructing buildings, roads, and heavy boundary walls. This has led to the blockage of rainwater on the hills. Consequently, the improper drainage system has increased the frequency of landslides in the Kharghuli Hill region. Proper drainage is necessary to ensure the flow of water from the hills and mitigate landslide risks.

3.7. Seismicity

The north-east part in India, along with its adjacent areas, frequently experiences seismic activity, leading to frequent earthquakes. This region encompasses diverse geological features. Previous research efforts have primarily focused on studying significant earthquakes that have occurred in this area.

Earthquakes are a common occurrence in northeast India, although their intensity can vary, ranging from 5 to 8 or even higher on the Richter scale. Earthquakes with magnitudes below 5 are scattered across the region. However, earthquakes with magnitudes surpassing 5 are predominantly observed in the northernmost part of Arunachal Pradesh and certain areas of the lower Brahmaputra Valley.

According to India seismic hazard zonation map, north-east region of India falls within Zone V, which is classified as a high seismic hazard zone.

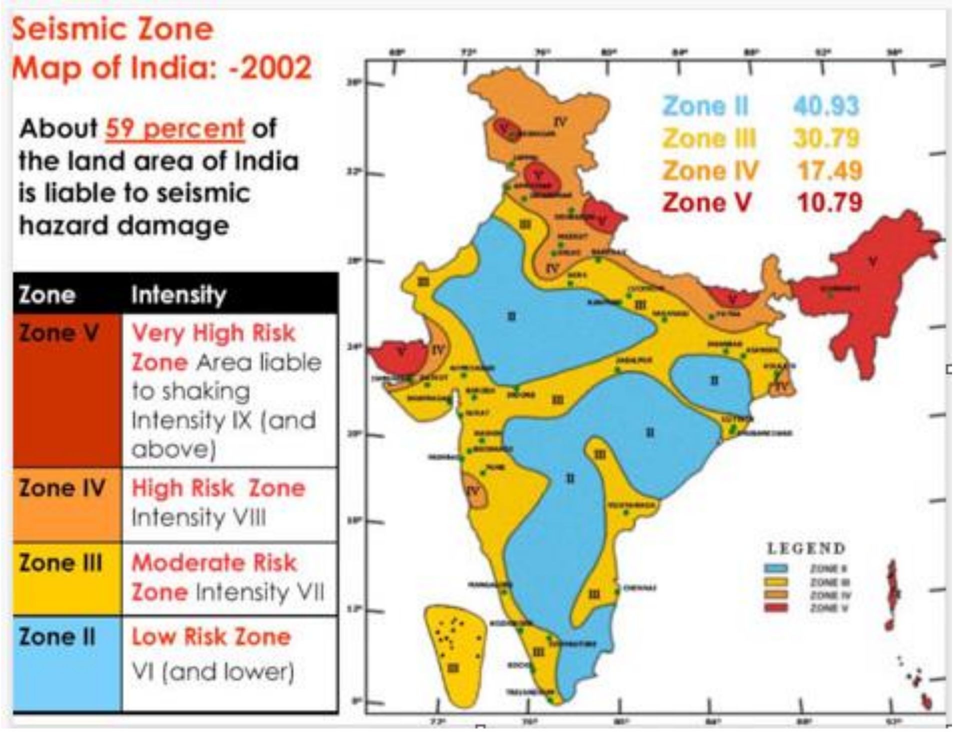

Figure 3-3 Seismic Zone Map of India

Chapter-4: DESIGN DATA

4.1. Slope Geometry and stratification

The natural slope being analysed is depicted in Figure 4-1. It has an approximate height of 44m and is accompanied by an existing road and a few buildings at its top. To determine the stratification of the slope, three boreholes were considered at the hilltop, road level, and a few meters above the toe of the slope.

Based on the available information and engineering judgement, the following stratification has been established for the slope, which will be used for further analysis:

- **Layer-1:** Overburden soil-1
- **Layer-2:** Overburden soil-2
- **Layer-3:** Medium Strength Gneiss Rock
- **Layer-4:** High Strength Gneiss Rock

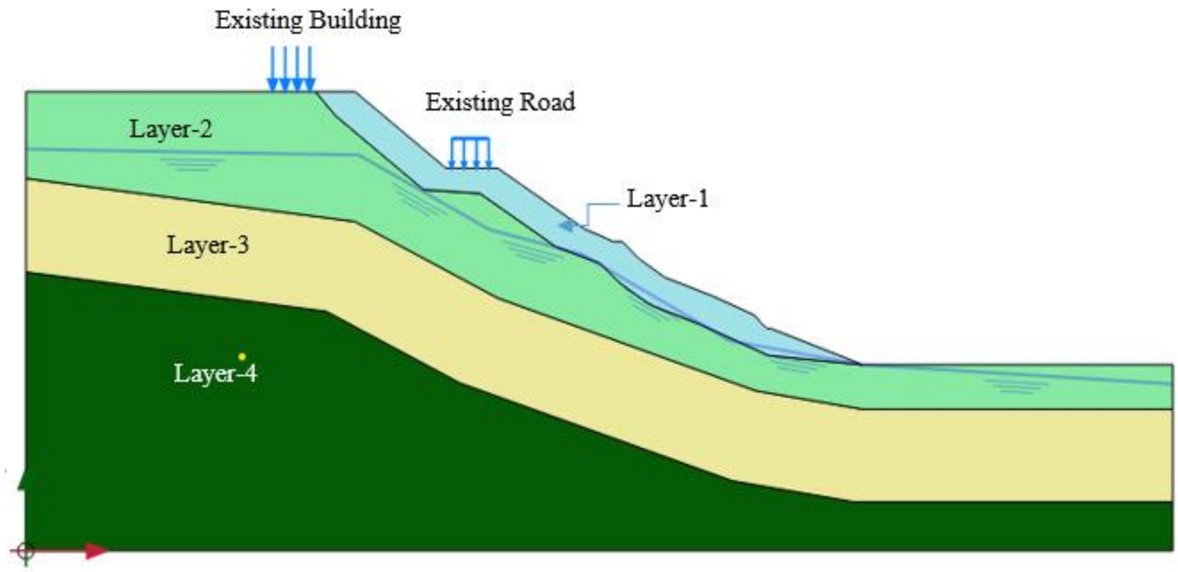

Figure 4-1 Slope Geometry and Stratification

4.2. Geotechnical Data

Several iterations were conducted using the back-analysis technique to obtain design parameters that accurately reflect the in-situ conditions.

The geotechnical parameters used for the final analysis are presented in Table 4-1 below:

Table 4-1 Geotechnical Parameters

S. No.	Strata	Density	Cohesion	Angle of Internal Friction φ	Young's Modulus	Poisson's Ratio
		kN/m3	kPa	°	MPa	
1	Overburden Soil-1	18.5	8	25	100	0.4
2	Overburden Soil-2	19.5	28	28	200	0.4
3	Medium Strength Gneiss Rock	24	150	30	1000	0.35
4	High Strength Gneiss Rock	27	200	40	2000	0.3

4.3. Seismic Parameters

As per IS 1893, the horizontal seismic coefficient A_h for any structure is calculated using below formula.

$$Ah = \frac{(\frac{Z}{2})(\frac{Sa}{g})}{(\frac{R}{I})}$$

$$Av = \frac{2}{3}A_h$$

Where,

Z = Seismic zone factor

I = Importance factor for the corresponding structure

R = Response reduction factor for the corresponding structure

$\frac{Sa}{g}$ = Design acceleration coefficient for different soil types

The project area lies in Seismic Zone-V. The seismic parameters for Zone-V corresponding to the hill slope are presented in table 4-2.

Table 4-2 Seismic Parameters corresponding to Hill Slope in Seismic Zone-V

Z	I	R	S_a/g	A_h	Av
0.36	1.2	3	2.5	0.18	0.12

The above horizontal and vertical seismic coefficients have been used in the analysis for all the calculations.

4.4. Design FOS

As per IS 14243 (Part-2): 1995, the minimum design FOS of natural slopes is presented in table 4-3 below:

Table 4-3 Design FOS

S. No.	Slope Type	Static FOS	Dynamic FOS
1	Soil Slope/Talus/Debris Slopes	1.5	1.2
2	Rock Slopes	1.2	1.0

4.5. Surcharge Load

Surcharge Load of 24 kPa and 50 kPa is considered in the analysis for the existing road and existing building, respectively.

4.6. Support System Properties

Self-Drilling Anchor (SDA) Bolts of 38mm dia along with 5 strand Cable Anchors and micro-pile have been adopted as Support System for current studies.

4.6.1. Self-Drilling Anchors (SDA)

Self-Drilling Anchors, alternatively referred to as Hollow Bar Anchors, are employed to stabilize unstable or collapsible soils without the requirement of a casing. These anchors are composed of steel bars with complete threading that can be drilled and injected with grout into the ground. The steel bar possesses a hollow core, enabling the passage of flushing and grouting materials during the installation process. Hollow Bar Anchors exhibit suitability for a diverse array of soil and ground conditions, including sand, gravel, irregular fill, boulders, rubble rock, footings, and base slabs.

Table 4-4 SDA Properties

Diameter	38 mm
Bolt Type	Fully Bonded
Bolt Modulus	200 GPa
Yield Capacity	400 kN
Length	10 m
Spacing	3m (Vertical) X 2m (Out of Plane)

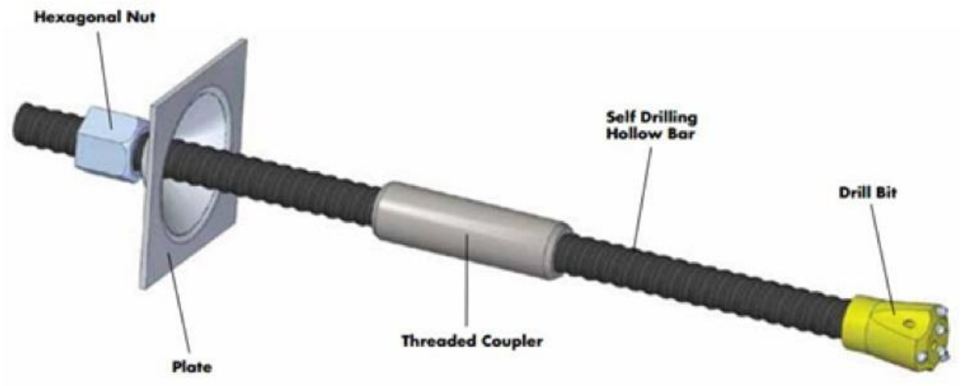

Figure 4-2 Self-drilling Anchor

4.6.2. Cable Anchors

Cable anchors are a form of soil reinforcement system designed to provide active support to unstable ground by exerting pre-stressing force on the cables. The cable anchor's overall length is comprised of two parts: a fixed length section and a free length section.

By applying pre-stressing force, the fixed length section of the cable anchor activates the bond strength, establishing a secure connection within the soil. Simultaneously, the pre-stressing force induces strains within the free length section of the cable. This activation process creates a cone-shaped region of stress within the slope, which effectively hinders the development of failure surface and enhances the slope’s stability.

Table 4-5 Cable Anchor Properties

Borehole Diameter	125 mm
Strand Diameter	15.20 mm
Total number of strands	5 nos.
Bolt Type	50% backend bonded
Bolt Modulus	200 GPa
Yield Capacity	600 kN
Bond Strength	200 kN/m
Free Length	20 m
Fixed Length	10 m
Spacing	3m (Vertical) X 2m (Out of Plane)

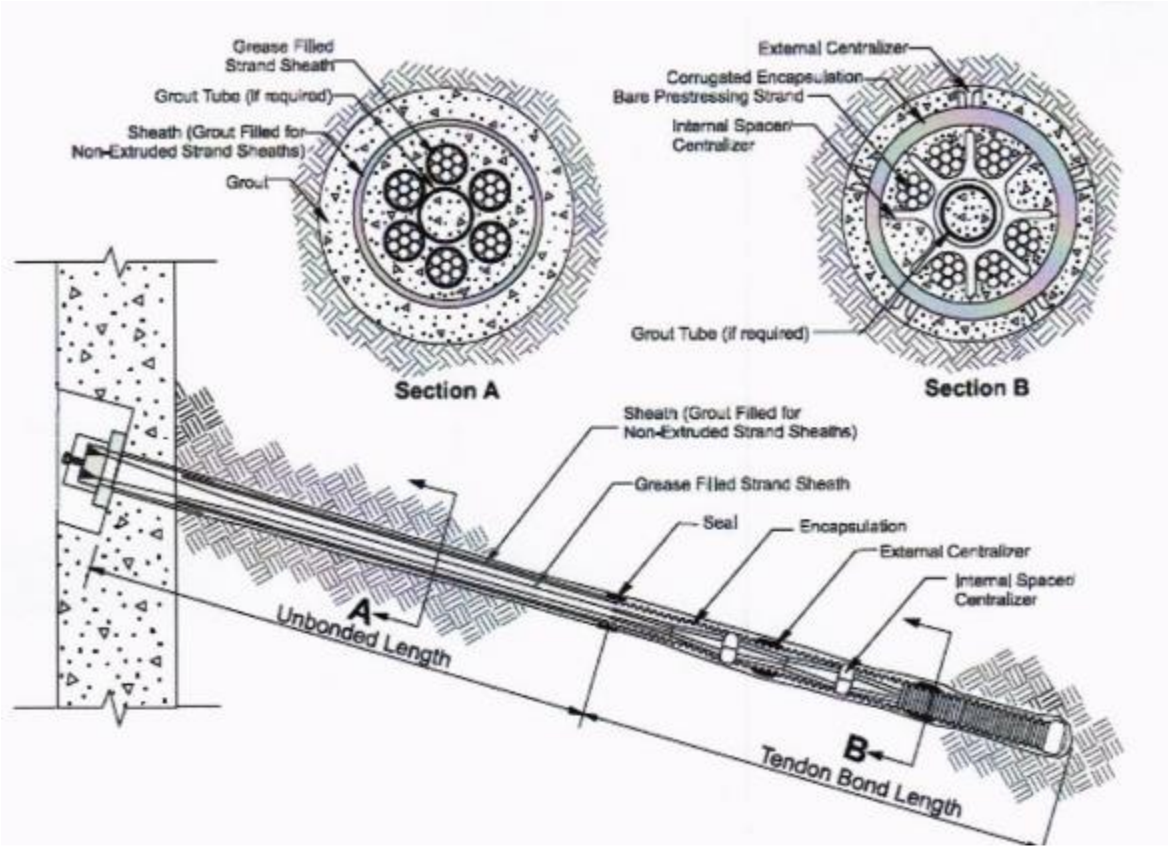

Figure 4-3 Schematic diagram of a Cable Anchor (Ref FHWA)

4.6.3. Micro-Piles

Micro piles are small-diameter, high-strength piles that are utilized in slope stabilization to enhance the stability of soil. These piles are typically made of steel or concrete and are installed into the ground using specialized drilling techniques.

Micro piles serve multiple purposes in slope stabilization. Firstly, they provide additional support to the slope by transferring the load the unstable layer to deeper, more stable layers. By implementing these measures, the forces exerted on the slope are effectively redistributed, thereby mitigating the potential risk of slope failure.

Secondly, micro piles can improve the global shear strength of the material soil. By reinforcing the soil mass, they increase its resistance to sliding and provide additional cohesion and friction. This helps to prevent soil movement and instability.

Micro piles also offer advantages in terms of their flexibility and adaptability. Their small diameter allows for installation in confined spaces or areas with limited access. They can be installed at various angles, depending on the specific slope conditions and engineering requirements.

In our analysis, the micro piles are combined cable anchors, to create a comprehensive and effective stabilization system. They can be designed and tailored to suit the specific soil characteristics and slope conditions, ensuring optimal performance and long-term stability.

Overall, the use of micro piles in slope stabilization helps to mitigate the risks associated with unstable slopes, providing structural reinforcement and enhancing the overall stability of the soil mass.

Table 4-6 Micro-pile Properties

Borehole Diameter	500 mm
Pile Length	25 m
Spacing	2m (Out of Plane)

4.7. Load Cases

Following load cases have been considered in the analysis

4.7.1. Static Case

In static case, the following loads have been considered in the design

(a) Ground Load - Gravity loading

(b) Water Load - Using phreatic level

(c) Surcharge Load - UDL Loads

4.7.2. Dynamic Case

In dynamic case, the following loads have been considered in the design

(a) Ground Load - Gravity loading

(b) Water Load - Using phreatic level

(c) Surcharge Load - UDL Loads

(d) Earthquake Load – Pseudo static analysis

***Ground Water Table (GWT)** has not been encountered in any of the boreholes and also Lugeon values of existing overburden strata has been encountered as 0.13x10-3 cm/sec to 0.63x10-3 cm/sec which ascertain that the existing strata is free draining material. But keeping in mind worst case scenario, Ground Water Table (GWT) has been assumed in design since most of the existing weep holes in the area are choked, not maintained and the area lacks presence of any proper drainage of water through surface and sub-surface drains.

4.8. Software and Analysis Approach

The below section provides and overview about the two softwares used in the current study.

4.7.1 Talren - LEM

TALREN is a highly regarded commercial 2D software program by Terrasol used for assessing the stability of different slopes, including:

- natural slopes
- cut or fill slopes
- earth dams
- dikes.

It offers comprehensive analysis considering different reinforcement options such as anchors, nails, struts, strips, etc.

TALREN utilizes the principles of limit equilibrium calculation along potential failure surfaces using methods such as Fellenius, Bishop, or perturbations. It can handle both plain strain and axisymmetric problems, taking into account typical hydraulic conditions. Additionally, the software can incorporate seismic loads through the Pseudo static method, which involves considering horizontal and vertical acceleration coefficients specific to the region.

Figure 4-4 Terrasol Talren LEM Software

4.9. Plaxis 2D - FEM

Plaxis 2D is a widely used software by Bentley for geotechnical design, utilizing the FEM modelling. It is commonly employed for designing underground excavations, flow analysis and dewatering design, slope stability analysis, and designing tunnels, among other applications. As mentioned earlier, Plaxis 2D utilizes the Strength Reduction technique, a.k.a. the "c-phi" reduction technique, calculating Factors of Safety.

The software adopts a plain strain model and employs meshing elements for the analysis. While Plaxis 2D offers the flexibility to consider various material models, the current study specifically utilizes the Mohr-Coulomb failure criterion to ensure comparable results with the Limit Equilibrium Method (LEM).

Figure 4-5 Bentley’s Plaxis 2D FEM Software

Chapter-5: RESULTS AND DISCUSSIONS

In this chapter, the outcomes of the analysis conducted using LEM and FEM, specifically focusing on the Factor of Safety are presented. The analysis explores various loading and support system conditions to assess the stability of the slope.

Furthermore, this chapter includes discussions based on the analysis results and addresses the practical applications of support systems in the field. These discussions shed light on the effectiveness of different support systems in improving slope stability and mitigating potential risks.

5.1. LEM Results

In this section, the software screenshots from Talren that demonstrate the Factor of Safety calculated using the Bishop's Method of analysis are provided. These screenshots serve as visual representations of the results obtained from the software, showcasing the computed Factor of Safety values.

This visual representation aids in the interpretation and analysis of the slope stability results, contributing to a comprehensive understanding of the analysed slope's stability characteristics.

5.1.1. Present Condition – Unsupported Slope

(a) Static Case

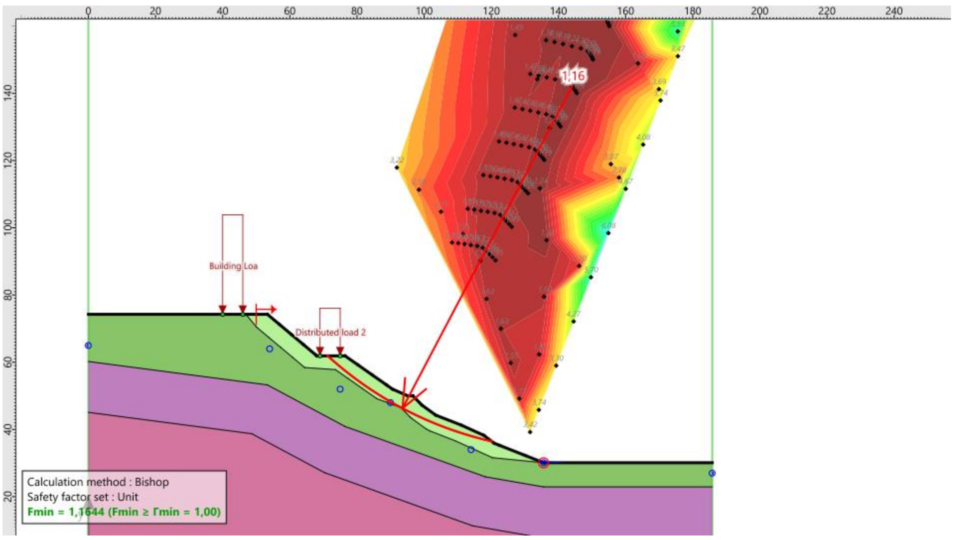

Figure 5-1 LEM Static Case FOS- Unsupported

(b) Dynamic Case

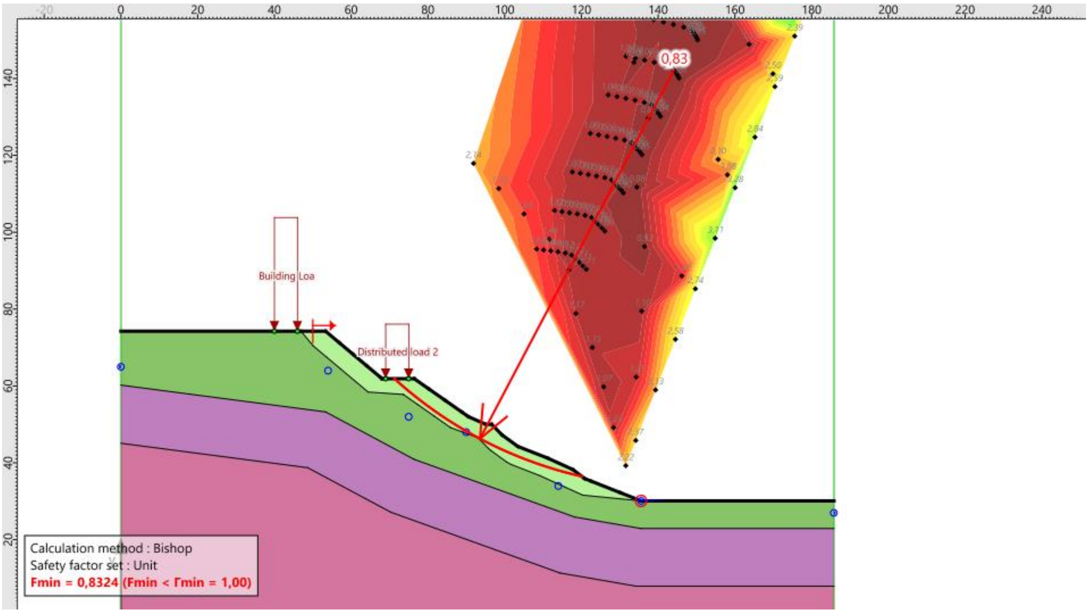

Figure 5-2 LEM Dynamic Case FOS- Unsupported

5.1.2. Reinforced Slope Condition

(a) Static Case

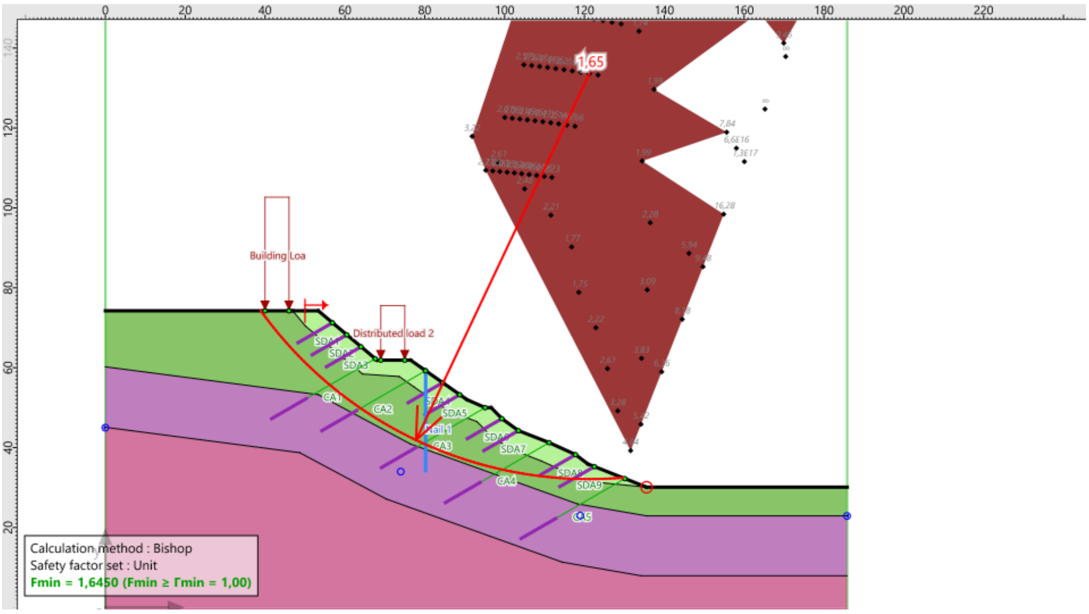

Figure 5-3 LEM Static Case FOS- Supported

(b) Dynamic Case

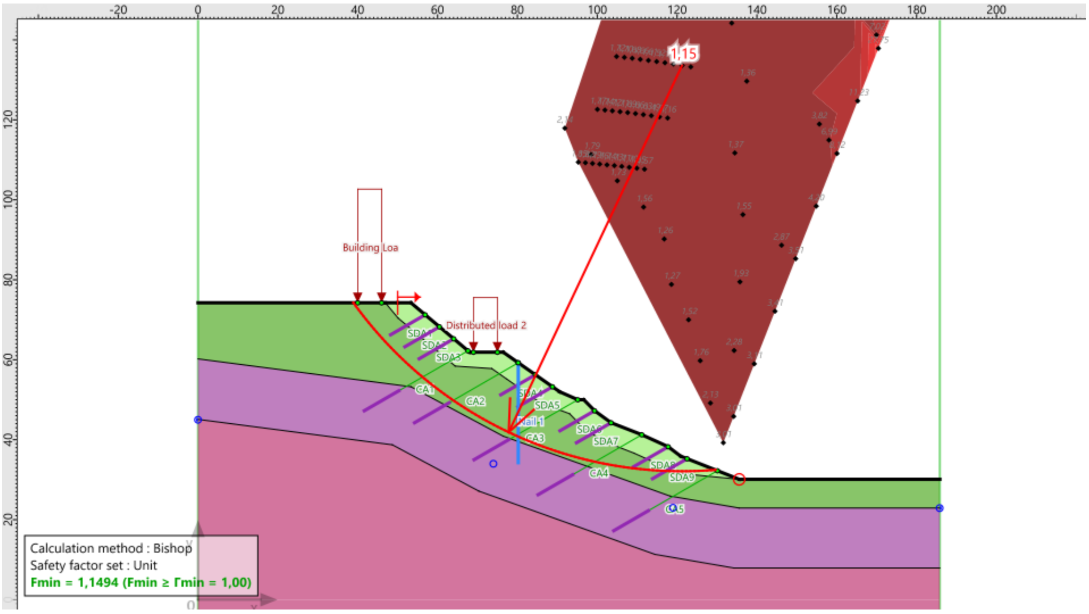

Figure 5-4 LEM Dynamic Case FOS- Supported

The factor of safety obtained from the LEM analysis is displayed in the following table, labelled as Table 5-1.

Table 5-1 Factor of Safety from Limit Equilibrium Analysis

S. No.	**Load Case**	**Factor of Safety**	
		Without Support	**With Support**
1	Static	1.16	1.65
2	Dynamic	0.83	1.15

5.2. FEM Results

In this section, the software screenshots from Plaxis 2D that demonstrate the Factor of Safety calculated using the "Strength Reduction" or "c-phi reduction" method are provided. These screenshots serve as visual representations of the results obtained from the software, showcasing the computed Factor of Safety values.

This visual representation aids in the interpretation and analysis of the slope stability results, contributing to a comprehensive understanding of the analysed slope's stability characteristics.

5.2.1. Present Condition – Unsupported Slope

(a) Static Case

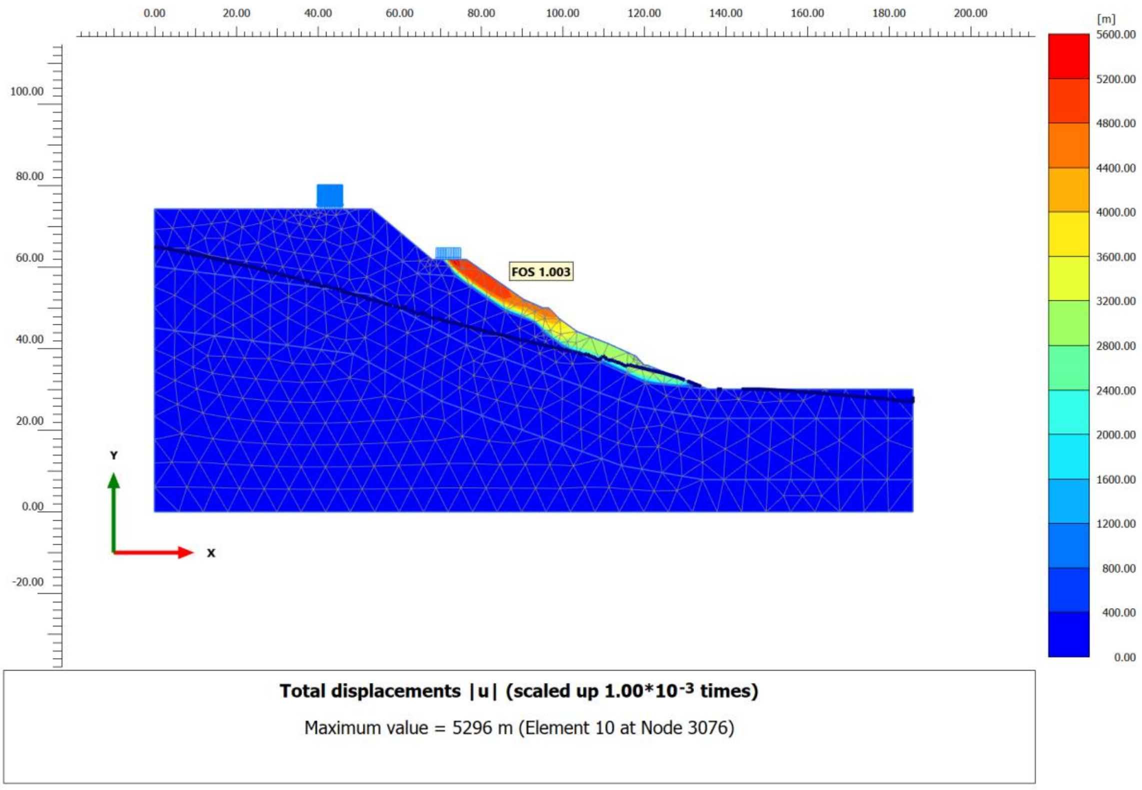

Figure 5-5 FEM Static Case FOS- Unsupported

(b) Dynamic Case

The model did not converge considering the Pseudo-static analysis in present unsupported condition.

5.2.2. Reinforced Slope Condition

(a) Static Case

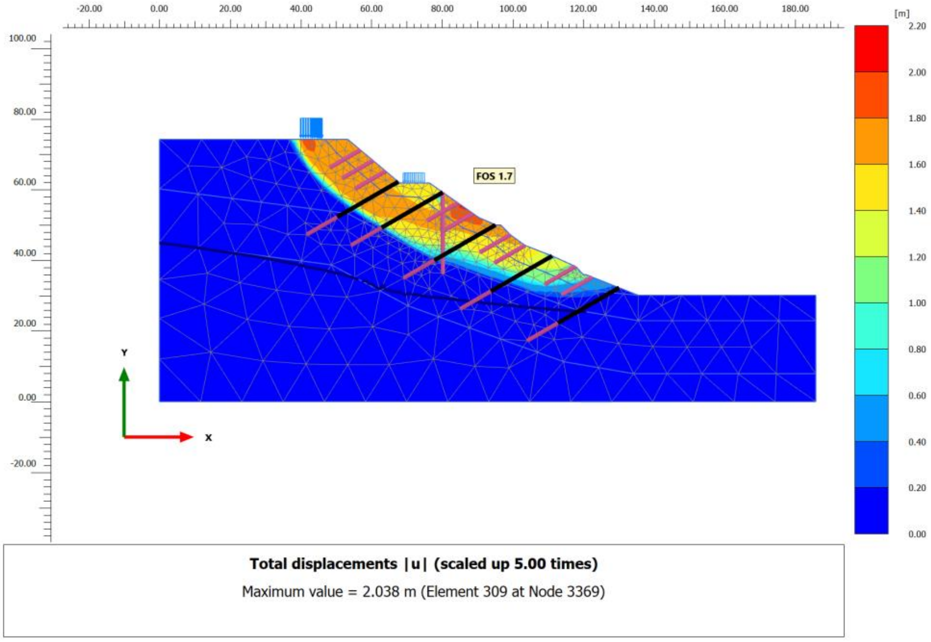

Figure 5-6 FEM Static Case FOS- Supported

(b) Dynamic Case

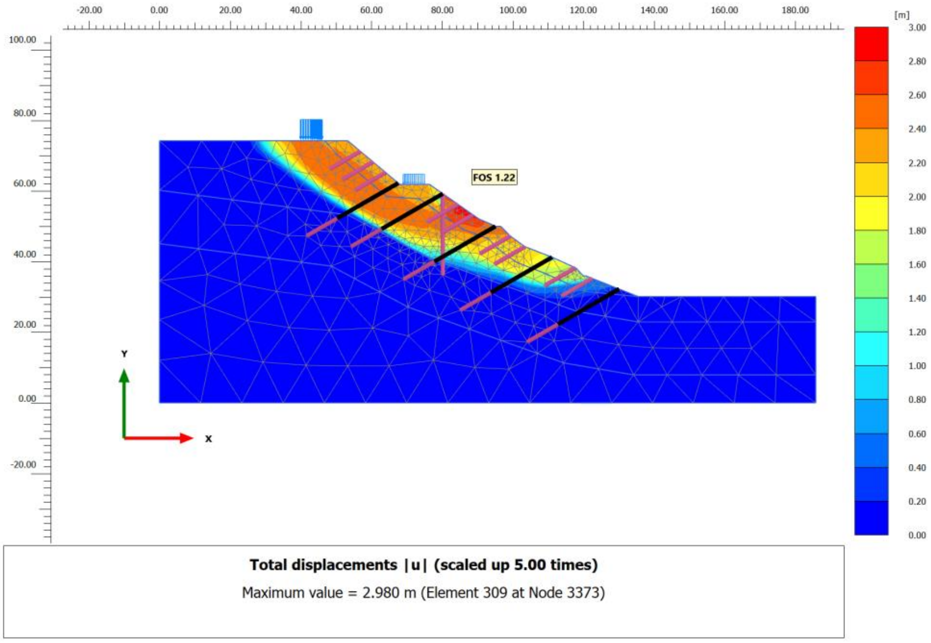

Figure 5-7 FEM Dynamic Case FOS- Supported

The factor of safety obtained from the FEM analysis is displayed in the following table, labelled as Table 5-2.

Table 5-2 Factor of Safety from Finite Element Analysis

S. No.	**Load Case**	**Factor of Safety**	
		Without Support	**With Support**
1	Static	1.003	1.7
2	Dynamic	-	1.22

5.3. Discussions

The global instability of the current slope under seismic conditions is evident from both analyses. To achieve the desired factor of safety, the slope is modified by implementing a support system as described above. In addition, the following measures and factors should be considered at the site:

(a) Surface Smoothening:

Before installing SDAs, the site should undergo surface smoothening. The entire area should be levelled, and benches should be created at intermediate levels whenever possible to enhance the local stability of the slope.

(b) Surface Protection:

To prevent localized slope failures, it is recommended to utilize High Tensile DT Mesh in conjunction with an Erosion Control Coir Mat. The coir mat assists in establishing vegetation, whose roots help bind the soil and prevent water infiltration. Wire Mesh, a double twisted wire mesh, can be draped over the slope area and anchored with SDAs.

Figure 5-8 High Tensile DT Mesh

(c) Drainage:

Implementing effective drainage measures is crucial for managing water and addressing slope stability issues. It is the key aspect that demands significant attention in most slope stability problems.

- Weep Holes: Install 100mm diameter weep holes at 3m intervals to channel rainwater to side drains. These holes should consist of perforated PVC pipes.

- Toe Drain: Establish and maintain a toe drain system to prevent water from entering the foundation area.
- Sub-surface Drainage Holes: Create 45mm diameter drainage holes at a grid of 3x3m on the slope area to drain infiltrated sub-surface water, preferably geotextile wrapped in PVC pipes.

(d) Instrumentation:

Geotechnical and structural instrumentation plays a vital role in monitoring slope performance and mitigating potential issues. The following instruments can be installed for monitoring purposes:

- Vibrating Wire Piezometers: Measure pore pressures within the slope.
- Digital Inclinometers: Monitor inclination within boreholes and provide early warnings for slope movements that may lead to failure.
- Settlement Gauges: Measure surface settlements to detect any movements that could result in slope failure.

Chapter-6: Comparing FEM and LEM

In this chapter, we explore and compare the practical challenges involved in modelling and analysing Finite Element Method (FEM) and Limit Equilibrium Method (LEM) tools. We examine the difficulties encountered when utilizing these methods and highlight their differences in terms of application and analysis.

6.1. Finite Element Analysis- Plaxis 2D

Below are some of the advantages and disadvantages of FEM experienced during the course of current study:

6.1.1. Advantages of FEM:

(a) Flexibility in Material Models: Finite Element Method (FEM) allows for the use of different material models to represent various soil or rock types. This includes models such as Mohr-Coulomb, Strain Hardening, Hoek and Brown, among others. This flexibility enables more accurate simulations that consider the specific behaviour of different materials.

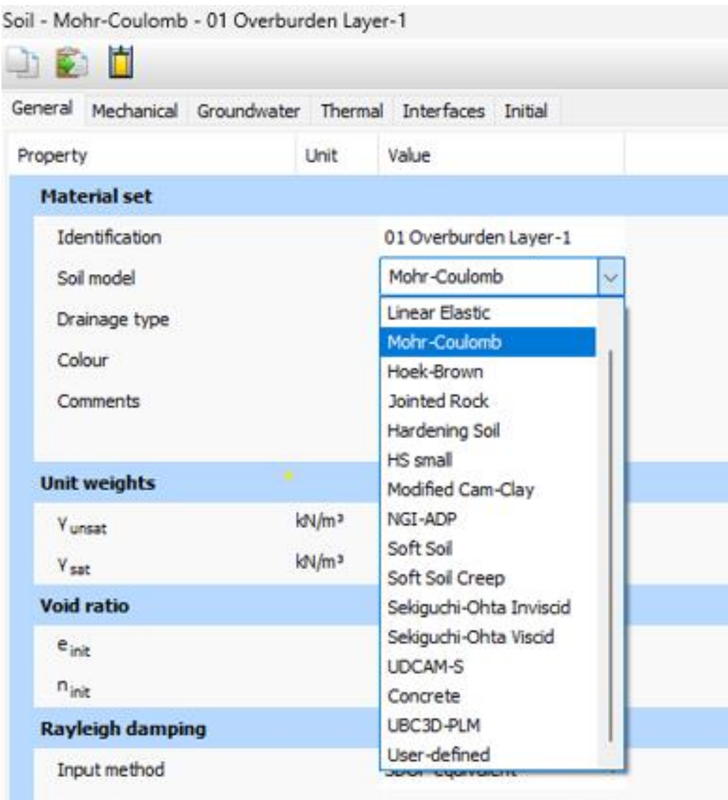

Figure 6-1 Different Material Models available in Plaxis 2D

(b) Deformation Representation: FEM provides a good representation of deformations within the soil mass. It allows for the analysis of the magnitude and distribution of deformations, which can be valuable in understanding the response of the slope or structure under different loading conditions.

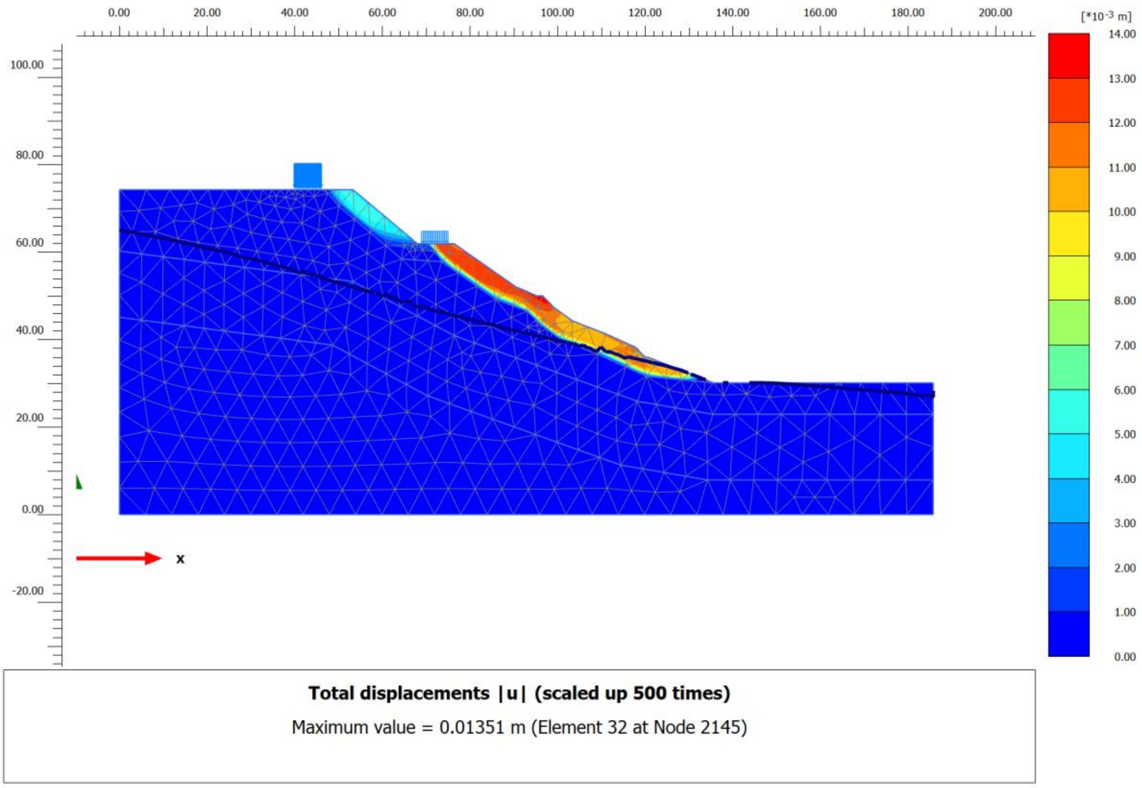

Figure 6-2 Deformation Representation in Plaxis 2D

(c) No Assumptions on Slip Surfaces: Unlike some other analysis methods, FEM does not require assumptions regarding slip surfaces. The method allows for the determination of critical failure mechanisms without assuming specific predefined failure surfaces. This enhances the accuracy of the analysis.

(d) Construction Stages: Plaxis 2D offers the capability to establish multiple construction stages, with each stage dependent on the preceding one. This feature enables the assessment of the slope's stability at each construction phase, ensuring verification of its stability throughout the construction process.

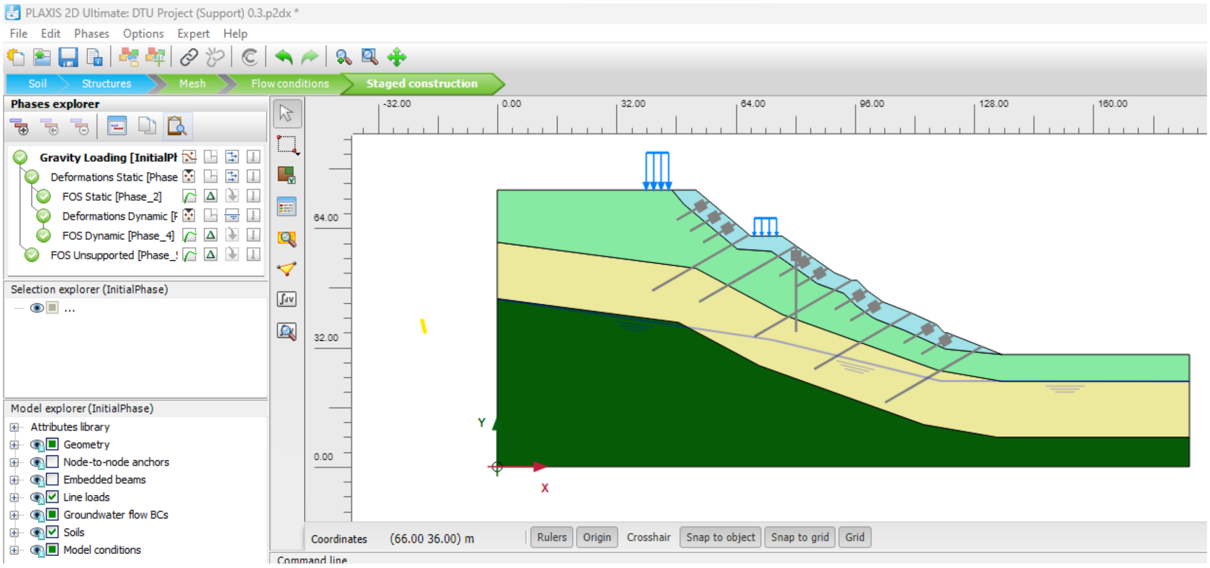

Figure 6-3 Construction Stages in Plaxis 2D

6.1.2. Disadvantages of FEM:

(a) Modelling Complexity and Meshing: FEM can be challenging to model due to its inherent complexities. Setting up an FEM analysis requires creating a suitable mesh, which can be time-consuming and technically demanding. The accuracy and reliability of the analysis results depend on the quality and refinement of the mesh.

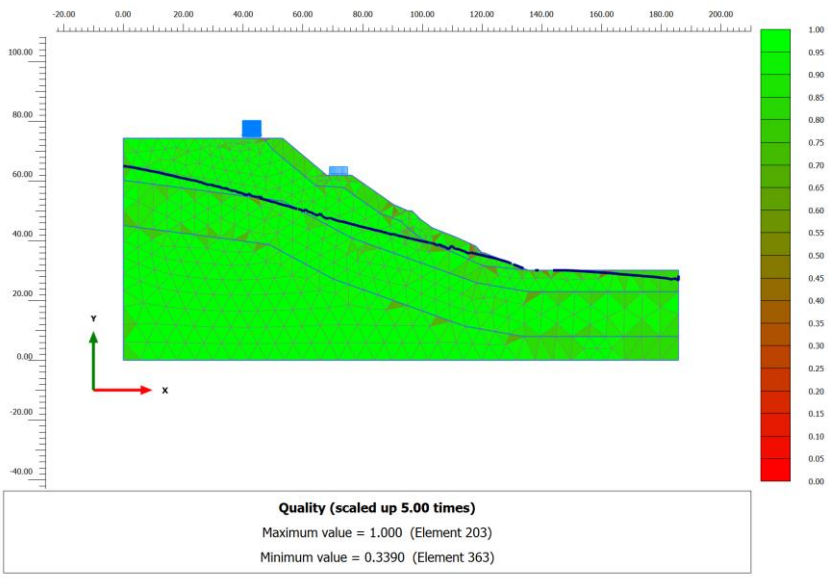

Figure 6-4 Meshing in Plaxis 2D

(b) Convergence Problems: In some cases, localized convergence problems may arise during FEM analysis. These problems can occur when the model fails to converge to a solution due to factors such as complex soil behaviour, geometric irregularities, or inadequate numerical settings. Resolving convergence issues may require adjustments to the model or the analysis parameters.

(c) Limitations in Factor of Safety Visualization: FEM analysis typically highlights the most critical slip circle based on the location of maximum deformations. This means that other potential failure mechanisms or slip circles may not be explicitly visualized. Additionally, FEM models are unable to display factors of safety less than 1, as the analysis may not converge in such cases.

6.2. Limit Equilibrium Analysis- Talren

Below are some of the advantages and disadvantages of LEM experienced during the course of current study:

6.2.1. Advantages of LEM:

(a) Ease of Modelling and Analysis: Limit Equilibrium Method (LEM), specifically using software like Talren, offers a simpler and less time-consuming approach for modelling and conducting stability analysis. It requires fewer computational resources and can be more straightforward to set up, especially for relatively simple slope geometries.

(b) Visualization of Slip Circles and Factor of Safety: LEM allows for the visualization of different slip circles corresponding to different factors of safety. This capability enables a comprehensive understanding of the stability conditions within the slope. The slip circles can be filtered based on upper and lower factor of safety limits, providing better presentation and analysis options.

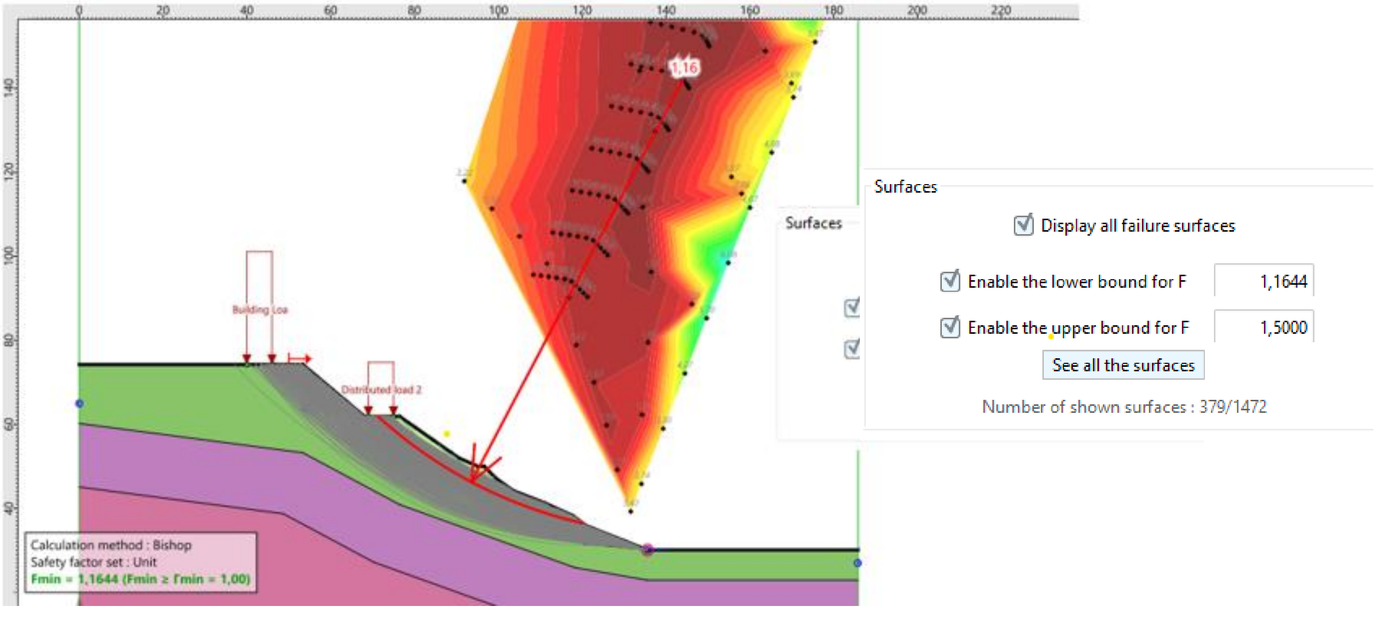

Figure 6-5 Visualization of Slip Circles and Factor of Safety

6.2.2. Disadvantage of LEM -

(a) Limited Material Model Options: LEM, particularly in software like Talren, typically only allows for the use of the Mohr-Coulomb material model. While this model is widely used and suitable for many applications, it may not accurately capture the behaviour of certain complex soil or rock types that require more advanced constitutive models. Therefore, LEM's applicability is limited to the Mohr-Coulomb model when using Talren or similar software.

(b) Assumptions for Circle Type and Slice Parameters: LEM requires specific assumptions to be input regarding the type of slip circle to be analysed, intervals for defining the slip circle, the number of slices to be considered, the emergence point of the slip surface, and other relevant parameters. These assumptions influence the accuracy and reliability of the analysis results. Careful consideration and expertise are required to make appropriate assumptions that reflect the actual conditions and behaviour of the slope.

(c) No option for Construction Stages: Unlike FEM, LEM analysis does not provide specific options for step-wise construction stages. In LEM, each construction stage is independently calculated without the ability to explicitly define and analyse the behaviour of the slope in a sequential manner.

It's significant to understand that while LEM has its limitations, it remains a widely used and valuable method for slope stability analysis, especially for simpler slope geometries and cases where the Mohr-Coulomb material model adequately represents the soil or rock behaviour. For more complex scenarios or when considering advanced constitutive models, FEM or other numerical methods may be more suitable. The selection of the analysis method relies on the particular project requirements and the desired level of accuracy.

Chapter-7: KEY CONSIDERATIONS FOR A SLOPE STABILITY PROJECT

When tackling slope stability problems, it is imperative to conduct meticulous on-site investigations and gain a deep understanding of the geological conditions present at the site. This involves examining various factors such as soil composition, rock layers, and groundwater conditions. By thoroughly comprehending these aspects, it becomes possible to identify the potential causes of slope failures and determine areas that are most susceptible to instability.

Additionally, analysing the drainage patterns within the slope is crucial. Understanding how water flows and accumulates within the slope helps in recognizing areas where excess moisture can weaken the slope and trigger instability. This includes considering factors such as rainfall patterns, surface runoff, and underground water flow.

By integrating all the gathered information, a site-specific protection scheme can be devised. This scheme aims to develop a solution tailored to the unique conditions of the slope in question. It involves evaluating various protective measures such as retaining walls, slope reinforcement techniques, or surface drainage systems. Assessing the feasibility and economic viability of these measures ensures that the selected protection scheme effectively mitigates the slope stability issues while being cost-effective.

Overall, a comprehensive understanding of the site's geology, potential failure causes, vulnerable areas, and drainage pathways is crucial for developing a well-informed and optimized site-specific protection scheme.

7.1. Topography Survey:

A comprehensive topography survey is essential to accurately determine the slope geometry at a site and prepare precise cross-sections. These cross-sections are crucial for conducting stability analysis. In standard engineering practice, it is recommended to select critical sections at intervals of approximately 25 meters to assess the slope height and angle. By adhering to this practice, a thorough understanding of the slope's characteristics can be obtained, aiding in reliable stability assessments.

7.2. Geological Investigations:

Geological investigations play a crucial role in project planning and assessment. It is imperative for a proficient engineering geologist to conduct an on-site visit, thoroughly analyse the geological conditions, and identify outcrops, potential failure zones, and drainage paths. These investigations provide a preliminary assessment of the project, enabling a better understanding of the geological context and informing subsequent decision-making processes.

7.3. Geotechnical Investigations:

The geotechnical investigations encompass the following activities:

(a) Employing drilling techniques and ensuring accurate logging of obtained samples according to IS Standards by a skilled geologist.

(b) Performing in-situ tests, including the Standard Penetration Test (SPT), recording N values, conducting permeability tests, and evaluating in-situ properties.

(c) Collecting representative samples from SPT and UDS (Undisturbed Sampling) methods and conducting extensive laboratory testing on soil and rock samples. This testing involves assessing physical properties, shear strength parameters, modulus of elasticity, and performing uniaxial compression tests.

(d) Utilizing empirical relations, such as employing software like Roclab, to establish correlations between laboratory test data and in-situ data.

(e) Conduct parametric studies and sensitivity analysis to understand the behaviour of the soil under different conditions.

7.4. Geophysical Investigations:

Geophysical investigations are vital in understanding the subsurface conditions and identifying key elements such as stratifications and potential water sources or aquifers. Techniques such as Seismic Refraction Surveys (SRT) and Electrical Resistivity Survey (ERT) are commonly used in geophysical investigations.

These geophysical techniques aid in creating sub-strata tomography, which provides a detailed understanding of the subsurface conditions. This information is particularly critical in areas where water plays a significant role in landslide occurrences. By identifying potential water sources and understanding the geological context, it becomes possible to assess and mitigate the risk of landslides more effectively.

7.5. Hydrological Studies and Drainage Network Design

Hydrological studies and drainage design are vital in slope stability analysis. They help assess and mitigate risks related to slope failures by considering key aspects:

- Water as a Triggering Factor: Excessive rainfall, runoff, and groundwater seepage increase pore water pressure, compromising soil strength and triggering instability.
- Quantifying Infiltration and Runoff: Hydrological studies quantify water infiltration and surface runoff, providing insights into water entry and pore water pressure that affect slope stability.
- Pore-water Pressure and Effective Stress Analysis: Water within a slope alters effective stress distribution, impacting soil strength. Analysing pore water pressure allows to assess water's influence on slope stability and determine necessary drainage measures.
- Designing Effective Drainage Systems: Well-designed drainage systems, such as surface or subsurface drains, control water flow and minimize pore water pressure build-up. Proper drainage mitigates the risk of slope failure caused by excess water.
- Preventing Erosion and Saturation: Hydrological studies identify erosion-prone and saturated areas. Erosion weakens soil, while saturation increases pore water pressure and reduces strength. Appropriate drainage measures minimize erosion and saturation risks, promoting slope stability.

Overall, hydrological studies and drainage design provide crucial information on water-related factors influencing slope behaviour. Effectively managing these aspects enhances slope stability and reduces the risks associated with slope failures.

7.6. Summary:

To effectively and accurately address slope stability problems, the utilization of computer-aided software, such as Finite Element Method (FEM) or Limit Equilibrium Method (LEM), proves highly beneficial. These software tools assist in simulating and analysing the complex behaviour of slopes under various loading and environmental conditions.

However, the accuracy and reliability of the software's output heavily depend on the input parameters that represent the actual site conditions. It is crucial to provide precise and reliable data regarding the slope's geometry, soil properties, groundwater conditions, and any other relevant factors that influence slope stability. The software relies on this information to perform calculations and generate meaningful results.

The selection of appropriate parameters is essential as it ensures that the software accurately models the real-world behaviour of the slope. Inaccurate or incorrect input parameters may lead to erroneous results and unreliable predictions, undermining the effectiveness of the software in addressing the slope stability problem.

Therefore, careful attention must be given to collecting and inputting reliable site-specific data into the software. This includes conducting thorough site investigations, utilizing geotechnical testing methods, and considering expert knowledge to determine the most accurate parameters. By doing so, the software can generate a fruitful output that aligns with the actual conditions of the slope, facilitating a more efficient and accurate resolution of the slope stability problem.

Chapter-8: CONCLUSIONS

The limitations of geotechnical limit equilibrium stability analysis methods arise from their inability to account for strain and displacement compatibility. Consequently, stress distributions obtained from these methods are unrealistic, and the consideration of local variations in safety factors is hindered. To overcome these limitations, it is necessary to incorporate a stress-strain constitutive relationship. Fortunately, there are now readily available and practical tools for conducting geotechnical stability analyses using finite element computed stresses. By combining the strengths of finite element methods (FEM) with familiarity of limit equilibrium methods, this approach offers improved accuracy and overcomes the limitations of traditional approaches.

According to research papers, FEM proves as dependable and strong technique for evaluating slope stability. The factor of safety is naturally determined without the need for assuming a specific failure mechanism. The discrepancies in the factor of safety between FEM and limit equilibrium methods are generally minimal. FEM allows for modelling non-linear stress-strain behaviour and enables stability analysis based on deformations. It eliminates the necessity of assumptions regarding slice side forces and does not require predetermined assumption regarding the shape or location of the failure surface. While limit equilibrium methods have been widely utilized in slope stability estimation, FEM offers significant advantages in addressing their limitations.

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