Identification of Landslide Zones At Mettupalayam To Udagamandalam Using GIS & Remote Sensing

S. Navaneetha[1], S. Raajamurugan[2]
[1]Dept of Environmental Engineering
[2]Dept of Civil Engineering
[1, 2] Gnanamani College of Technology, Tamil Nadu, India

Abstract- *Despite advancements in recognition, prediction, and preventive measures, landslides continue to cause significant social, economic, and environmental damage in the Nilgiris district, Tamil Nadu. This persistent issue stems from the complexity of slope failure mechanisms and our incomplete understanding of the underlying factors.*

In this study, four soil samples were collected from frequently affected landslide sites in the Nilgiris district and subjected to geotechnical analysis, including tests for cohesion, angle of friction, and Atterberg's limits. These soil properties were then used as input parameters for slope stability analysis conducted using Oasys Slope. Additionally, Scanning Electron Microscope (SEM) imaging and Energy Dispersive X-Ray Analyzer (EDX) testing were performed to further characterize the soil composition.

The landslide site's satellite imagery was obtained from Google Earth and converted into data points. Using TCX Converter and Quick Grid, the slope profile was plotted for analysis. Rainfall data from nearby rain gauge stations were also collected and incorporated into the study. Based on these inputs, the factor of safety was determined, and site-specific remedial measures were proposed. The findings from this study can guide the design and implementation of appropriate retaining structures to enhance slope stability and mitigate future landslides.

I. INTRODUCTION

A landslide, also known as a landslip or mudslide, is a form of mass wasting that encompasses various types of ground movements, including rockfalls, deep-seated slope failures, and shallow debris flows.

Landslides occur when a slope transitions from a stable to an unstable state, driven by multiple factors that may act independently or in India has witnessed several severe and fatal landslides in recent years, particularly in the Himalayas, which are highly susceptible to slope failures during the monsoon season from June to October. While natural factors such as intense rainfall and seismic activity contribute to landslides, human activities also play a significant role. Deforestation, uncontrolled excavation, rock blasting, large-scale construction, and vibrations from heavy machinery can destabilize slopes, increasing the likelihood of landslides. Among these, tree removal is particularly impactful, as it reduces soil cohesion and exacerbates erosion in landslide-prone regions.

Landslide-prone regions in India include the Western Ghats and Konkan Hills, the Eastern Ghats, the Northeast Himalayas, and the Northwest Himalayas. India ranks highest in landslide-related disasters across the Asian continent. While the Himalayan region experiences the most landslides in the north, the Nilgiris district is the most affected area in the south. Over the past two to three decades, the Nilgiris have witnessed at least five major landslides, resulting in significant loss of life. One of the most devastating events occurred in November 2009, when over 1,000 landslips were reported across the district, claiming 45 lives. A Geological Survey of India (GSI) study conducted two decades ago revealed that nearly 70% of the district's original forest cover had been cleared for agriculture, including vegetable and seasonal crop cultivation, as well as tea and plantation crops. This large-scale deforestation has significantly weakened slope stability, increasing the risk of landslides.

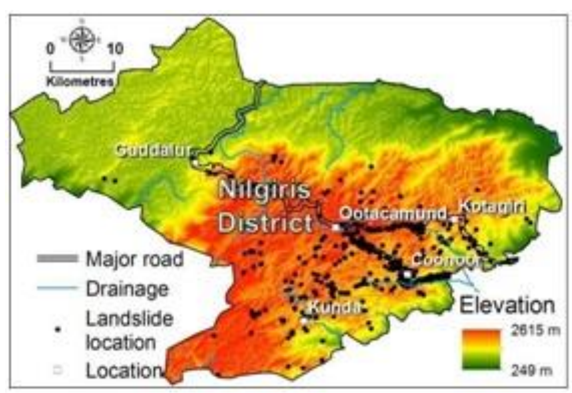

Fig 1.1 Map of Nilgiris District

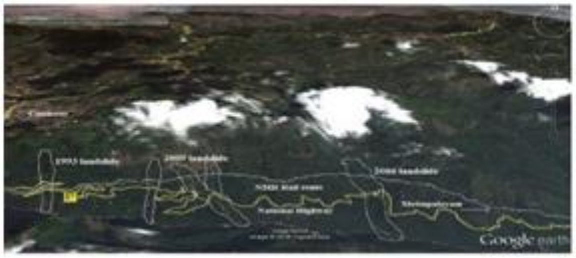

Fig 1.2 View of Mettupalayam –Coonoor road The primary trigger for landslides is prolonged and intense rainfall. Even moderate rainfall can induce slope failures if the duration is extended and pore pressure increases significantly. A global landslide survey conducted in 2003 revealed that 90% of landslides were initiated by heavy rainfall, primarily due to the rise in pore water pressure within the soil.

The Nilgiris district experiences heavy rainfall beginning in June each year. While the downpour benefits farmers, it also causes disruptions, particularly in Ooty and Gudalur, where landslides and tree falls are common during the monsoon season. One of the most severe landslide events occurred in November 2009 during the Northeast monsoon. Intense rainfall triggered landslides at over 300 locations, severely affecting road and rail traffic and destroying numerous buildings. The disaster left more than 50 people dead and displaced hundreds of residents.

The Mettupalayam–Coonoor–Ooty National Highway suffered multiple landslides, with some sections of the road completely washed away, cutting off access for nearly three months. The Nilgiris Mountain Railway (NMR), a UNESCO World Heritage Site, also sustained significant damage. For this study, four sites within this region have been selected for detailed investigation.

SCOPE AND OBJECTIVE

The Nilgiris district receives rainfall during both the southwest and northeast monsoons, with average annual precipitation ranging from 1,500 mm to 3,000 mm, depending on the location. In November 2009, the district recorded 547 mm of rainfall, the highest in thirty years for that month. Visual observations play a crucial role in landslide studies (Bhandari, 2006). As part of this study, a preliminary geotechnical investigation was conducted, including field assessments of the damage caused by landslides. While remedial measures are site-specific, the methodology used in this study can be applied to other landslide-prone areas in hilly terrains.

Although intense rainfall was the immediate trigger for landslides in many locations, several underlying factors contributed to slope failures. These include excavation at the slope toe, vertical cutting, excessive loading at the crest, poor surface drainage maintenance, and extensive human activities. The absence of an adequate subsurface drainage system further intensified the problem by increasing pore water pressure, a critical factor in landslide initiation.

A detailed geotechnical investigation is essential to propose effective, site-specific mitigation measures. To enhance slope stability and prevent future landslides, retaining walls can be designed based on the calculated factor of safety. This study aims to assess the depth of landslides and classify them accordingly, providing valuable insights for future slope stabilization efforts.

Literature review

LANDSLIDES IN NILGIRIS: CAUSAL FACTORS AND REMEDIAL MEASURES

S.S. Chandrasekaran, V.Senthilkumar, V.B. Maji

Landslides are a significant natural hazard, affecting approximately 15% of India's land area. The Himalayas and the Nilgiris are among the most landslide-prone regions in the country. In the Nilgiris, heavy rainfall serves as the primary triggering factor, whereas in certain Himalayan regions, landslides result from a combination of intense rainfall and seismic activity.

While rainfall is the immediate trigger, several underlying factors contribute to slope failures in the Nilgiris. Key causes include slope excavation at the toe, excessive loading at the crest, blocked surface drainage systems, clogged weep holes in retaining structures, poor planning and design, inadequate implementation of remedial measures, vegetation removal, and indiscriminate dumping. These factors, when combined with heavy rainfall, significantly increase the likelihood of landslides.

The study suggests that while retaining walls are commonly used as a mitigation measure, integrating cost-effective subsurface drainage systems with slope reinforcement could provide a more effective solution for landslide prevention in many areas. Additionally, this research provides an overview of numerical analysis techniques related to landslide assessment in the Nilgiris, alongside ongoing detailed site-specific geotechnical
investigations.

DAMAGES TO TRANSPORT FACILITIES BY RAINFALL INDUCED LANDSLIDES DURING NOVEMBER 2009 IN NILGIRIS, INDIA

S. S. Chandrasekar, S. Elayaraja, S. Renugadevi

The Nilgiris district, a renowned hill station in Tamil Nadu, India, has a long history of destructive landslides. This study presents field observations and preliminary geotechnical investigations on the impact of rainfall-induced landslides that occurred in November 2009, resulting in the loss of over fifty lives and leaving hundreds homeless.

Laboratory tests were conducted on soil samples collected from landslide-affected sites, revealing that the soils primarily consist of clayey sand and silty sand with high fine content and low permeability. Case studies documenting damage to roads, railways, and buildings are also discussed.

While heavy rainfall was the immediate trigger for these landslides, several underlying factors contributed to slope failures. These include excavation at the slope toe, vertical cutting, excessive loading at the crest, and inadequate maintenance of surface drainage systems.

USE OF QUANTITATIVE LANDSLIDE HAZARD AND RISK INFORMATION FOR LOCAL DISASTER RISK REDUCTION ALONG A TRANSPORTATION CORRIDOR: A CASE STUDY FROM NILGIRI DISTRICT, INDIA

Pankaj Jaiswal, Cees J. van Westen

The primary objective of hazard and risk analysis is to apply the findings in selecting effective landslide risk reduction strategies. However, the underutilization or non-utilization of these results in pre-disaster planning often arises due to challenges in interpreting the scientific content and implications of hazard models.

This study aims to demonstrate the practical applications of hazard and risk information in various landslide risk reduction strategies along a transportation corridor in the Nilgiris, India. It emphasizes the use of quantitative risk data in cost-benefit analyses for planning structural mitigation measures to safeguard road and railway alignments. Additionally, the study provides examples of how transportation agencies can implement these protective measures effectively.

Furthermore, the research highlights the role of hazard and risk assessments in spatial planning and zoning, identifying areas where landslide hazards are too severe to permit future developments.

EVALUATION OF SEISMIC HAZARD AND POTENTIAL OF EARTHQUAKE INDUCED LANDSLIDES OF THE NILGIRIS, INDIA

Elayaraja, S. S. Chandrasekaran, G. P. Ganapathy

The Nilgiris district in Tamil Nadu, India, has experienced frequent landslides in recent years. This study conducts a deterministic seismic hazard assessment for the region, considering a 350 km radius around the Nilgiris. A seismotectonic map was developed, detailing faults and historical earthquakes in the area. The peak ground acceleration (PGA) at the bedrock level and the response spectrum were evaluated, identifying the Moyar and Bhavani shear zones as the primary seismic sources for the region.

Ground response analysis was performed at seven sites in the Nilgiris using the one- dimensional equivalent linear method with the SHAKE 2000 program, accounting for topographic effects. The PGA of surface motion showed amplification, reaching 0.64 g in Coonoor and 0.44 g in Ooty, compared to an input motion of 0.39 g. Additionally, the bracketed duration of surface acceleration increased to 20 seconds in Coonoor and 18 seconds in Ooty, compared to the input motion duration of 8 seconds.

Seismic displacement analysis using Newmark's method revealed that five of the seven investigated sites exhibit moderate seismic landslide hazard, while Coonoor and Ooty are classified as high-hazard zones.

METHODOLOGY

IDENTIFICATIONOFPROBLEM
↓
LITERATUREREVIEW
↓
IDENTIFYINGSITELOCATION
↓
SOILSAMPLECOLLECTION
↓
LABORATORYTESTING
↓
DIGITALELEVATIONMODELING
↓
SLOPEANALYSIS(OASYSSLOPE)
↓
RESULTSANDDISCUSSION
↓
CONCLUSION

STUDY AREA

5.1 Achanakal

Achanakal is a village in the Nilgiris district of Tamil Nadu, India, situated along the Coonoor-Ooty highway in the Ketti Valley. The area experienced a major landslide on **November 9, 2009**, causing significant damage. The coordinates of the landslide-affected site are **Latitude: 11.38117, Longitude: 76.714005**.

During November 2009, a series of landslides struck Achanakal, destroying **1,890 houses** due to heavy rainfall. That month, the region received approximately **3,500 mm of rainfall**, triggering widespread slope failures.

Achanakal experiences rainfall from both the **southwest** and **northeast monsoons**. The southwest monsoon is more dominant, contributing nearly **50% of the total rainfall in the western region** and **40% in the eastern region**. The northeast monsoon, though moderate, accounts for approximately **40% of the annual rainfall**.

MARAPALAM

The hilly terrains area have been subjected to slope failure under the influence of variety of terrain factors and triggered by events such as extreme rainfall or tectonic movements.

Landslide is a frequently occurring phenomenon in the Nilgiri district because of High Intensity of Rainfall. Rainfall is one of the triggering factors of landslides. As expected the landslide prone areas of Marapalam falls under the steep slope category which clearly shows that a heavy rainfall is sufficient to make the rocks and boulders come hurtling down in these steep terrains, that's what happened in the recent landslide occurred in November 2006. The site usually receives rainfall during both south west and north east monsoon. The average rainfall in this region varies from place to place and in between 1500 mm to 3000 mm. In November 2009, the district received a rainfall of 1867 mm, which is the highest rainfall recorded in a period of thirty years.

Fig 5.2.1 During Landslide

Gandhinagar Bus Stop

Gandhinagar Bus Stop is a key transportation hub in **Ooty, Tamil Nadu**, serving as one of the main bus stations in **The Nilgiris district** alongside those in Coonoor, Kotagiri, and Gudalur. The bus stand is situated on land that was originally part of **Ooty Lake**, which was later reclaimed for infrastructure development. The **coordinates** of the landslide-affected area are **Latitude: 11.407965, Longitude: 76.771148**.

One of the primary causes of landslides in this region is the **blocking of natural water pathways along the hills**. Experts emphasize the urgent need to address **encroachments**, as they contribute significantly to slope instability. Unfortunately, whenever landslides occur near **unplanned settlements** or **encroached colonies**, the underlying causes are often overlooked. Instead of implementing **long-term solutions**, authorities resort to **temporary fixes**, such as covering the affected areas with sandbags. Due to the **lack of permanent mitigation measures**, these locations remain vulnerable to **recurrent landslides**.

Fig 5.3.1 During landslide

Madithorai

The **Madithorai** region experiences rainfall in two major seasons. The **southwest monsoon** is more dominant, bringing **heavy rainfall of approximately 620 mm**, while the **northeast monsoon** records significantly higher rainfall, reaching **79,280 mm**.

Rainfall is considered the **primary trigger** for landslides in the Nilgiris. The majority of landslides in this region are induced by **localized, short-duration, high-intensity rainfall** events. Variations in **mean, low, and heavy monthly rainfall** contribute to slope failures.

The **coordinates** of the study area are **Latitude: 11.403183, Longitude: 76.72422**. The region's **topography and geology** play a crucial role in landslide occurrences. The **Nilgiris Mountains** consist of numerous **spurs and branches extending in multiple directions**, with **narrow crests separated by deep gorges and valleys**. These valleys contain **high-velocity streams**, which rapidly transport runoff from the surrounding hills.

This complex **terrain and hydrology** make the area highly susceptible to **erosion and landslides**.

Fig 5.4.1 During Landslide

LABORATORY AND FIELD INVESTIGATION

Specific Gravity

Specific gravity (SG) is the ratio of the density of a substance to the density of a reference substance. It can also be defined as the ratio of the mass of a substance to the mass of an equal volume of the reference substance. For liquids and solids, the reference substance is water at its densest state (4°C or 39.2°F), while for gases, it is typically air at room temperature (20°C or 68°F).

The formula for specific gravity is: SG=Density of sampleDensity of waterSG =\frac{\text{Density of sample}}{\text{Density ofwater}}SG=Density of waterDensity of sam ple Specific gravity can be determined using various methods. One of the most common instruments for measuring the specific gravity of soil particles—both fine-grained and coarse- grained—is the pycnometer. A pycnometer is a specialized bottle designed to hold a precise, though not necessarily known, volume of liquid or solid material. It provides an accurate measurement of density and is widely used in geotechnical and soil mechanics studies.

SG =($W2 - W1$) − ($W3 - W4$) Where

W1= mass of empty Pycnometer

W2 = mass of the Pycnometer with dry soil

W3 = mass of the Pycnometer and soil and water W4 = mass of Pycnometer filled with water only. SG = Specific gravity of soils.

Wet Sieve Analysis

Sieve analysis, also known as a **gradation test**, is a method used to determine the particle size distribution of granular materials. This process can be applied to both organic and inorganic materials, including sand, crushed rock, clays, granite, feldspars, coal, and soil. The smallest particle size analyzed depends on the specific method used.

In **wet sieve analysis**, the procedure is similar to dry sieving, but with the addition of water to facilitate separation. The sieve stack is securely clamped onto a sieve shaker, and the sample is placed on the top sieve. A **water- spray nozzle** positioned above the top sieve assists in the sieving process by continuously washing finer particles through the mesh.

The rinsing process continues until the discharged liquid is clear. Any remaining sample residues on the sieves are carefully dried and weighed. It is essential to ensure that the sample does not undergo any physical or chemical changesF, isguc5h.4a.2s Pswreselelinntg C, ondition **dissolving, or reacting with the liquid**, which could affect the results.

The particle size distribution is typically represented on a **semi-logarithmic graph**, where:

Percentage finer is plotted on the **y-axis** (linear scale).**Particle size** is plotted on the **xaxis** (logarithmic scale). Key particle size parameters:

D_{10} (Effective Particle Size): The particle diameter for which **10%** of the sample is finer, and **90%** is coarser.**D_{50} (Median Particle Size):** The diameter for which **50%** of the particles are finer and **50%** are coarser.**D_{60}:** The diameter at which **60%** of the particles are finer and **40%** are coarser.

These values are commonly used to assess **soil gradation** and determine characteristics like **uniformity coefficient (Cu = D_{60}/D_{10})** and **coefficient of gradation (Cc = $(D_{30})^2$ / (D_{10} × D_{60}))**, which help in soil classification.

Coefficient of Uniformity (Cu)

The **uniformity coefficient (Cu)** is a measure of the range of particle sizes in a soil sample. It is defined as the ratio of **D_{60}** to **D_{10}**:

$$C_u = \frac{D_{60}}{D_{10}}$$

If **Cu > 4 to 6**, the soil is classified as **well-graded**, meaning it has a good distribution of different particle sizes.

If **Cu < 4**, the soil is considered **poorly graded (uniformly graded)**, meaning the particle sizes are more uniform with little variation.

6.2.2 Coefficient of Curvature (Cc)

The **coefficient of curvature (Cc)** is used to assess the shape and distribution of particle sizes. It is calculated using the formula:

$$C_c = \frac{(D_{30})^2}{D_{60} \times D_{10}}$$

For the soil to be **well-graded**, the **Cc** value should typically range between **1 and 3**.

A higher **Cu** indicates a **wider range of particle sizes**, contributing to better compaction and stability in soil structures

Atterberg Limits

The Atterberg limits define the critical water contents of fine-grained soils and are used to classify their consistency and behavior. These limits include the shrinkage limit (SL), plastic limit (PL), and liquid limit (LL), which determine soil states based on moisture content. Depending on its water content, soil can exist in one of four states:

Solid Semi-solid Plastic Liquid

Each state exhibits different engineering properties, making Atterberg limits essential for soil classification and construction applications. These limits help differentiate silt from clay and classify different types of silts and clays. Originally developed by Albert Atterberg, they were later refined by Arthur Casagrande for geotechnical applications**.**

Shrinkage Limit (SL)

The shrinkage limit (SL) is the water content at which further moisture loss no longer results in volume reduction of the soil. Beyond this point, the soil remains stable in volume despite continued drying.

Test standard: ASTM D4943

Usage: Less commonly used than plastic and liquid limits.

Plastic Limit (PL)

The plastic limit (PL) is the moisture content at which soil transitions from a plastic to a semi- solid state. It is determined by rolling a thread of soil on a flat, non-porous surface:

If the soil remains plastic, it can be rolled into a thin thread.
As moisture content decreases, the thread begins to crumble at a diameter of 3.2 mm (1/8 inch).
If a soil cannot be rolled into a 3.2 mm thread at any moisture level, it is classified as non- plastic (NP).

Test standard: ASTM D4318

Liquid Limit (LL)

The liquid limit (LL) is the moisture content at which soil transitions from a plastic to a liquid state. The change in behavior is gradual rather than sudden.
Determined using the Casagrande Liquid Limit Device:
Soil is placed in a metal cup.
A 2 mm wide groove is made down the center.
The cup is dropped 10 mm onto a rubber base at 120 blows per minute.
The number of blows required for the groove to close over 12.7 mm (0.50 in) is recorded.
The liquid limit is the moisture content at which 25 blows are needed to close the groove**.**

Plasticity Index (PI)

The **plasticity index (PI)** measures the range of water content in which a soil remains **plastic**. It is calculated as the difference between the **liquid limit (LL)** and the **plastic limit (PL)**:

PI=LL−PLPI = LL - PLPI=LL−PL

Soils with a **high PI** are typically **clayey** and retain plasticity over a wider moisture range.

Soils with a **low PI** are mostly **silty**, with limited plasticity.

Soils with a **PI of 0** are **non-plastic**, meaning they contain little or no clay or silt.

Soil Classification Based on PI

0 – Non-plastic
PI < 7 – Low plasticity
PI 7-17 – Medium plasticity
PI > 17 – High plasticity

Activity (A)

The **activity (A)** of a soil is defined as the **Plasticity Index (PI) divided by the percentage of clay-sized particles** (particles smaller than **2 µm**). Different types of clay minerals have varying **specific surface areas**, which influence the amount of water required for soil to transition between states, such as from plastic to liquid.

$$A = \frac{PI}{\%\text{ of clay fraction}}$$

The **activity value** helps identify the dominant **clay mineral** present in the soil.

High activity clays undergo significant **volume changes** when wetted and **shrink considerably** when dried, making them highly reactive.

Low activity clays exhibit minimal volume change and are less reactive chemically.

Clay Classification Based on Activity

0.75 to 1.25 – **Normal clay**
< 0.75 – **Inactive clay** (low reactivity and volume change)
> 1.25 – **Active clay** (high reactivity and significant volume change)

S. No	Sample Location	SL (%)	PL (%)	LL (%)	PI (%)	A	Soil Description
1	Achanakal	15.42	22.48	30.83	8.35	0.42	Medium Plastic& Inactive
2	Marapalam	12.14	23.81	29.12	5.31	0.29	Low Plastic& Inactive
3	GandhinagarBus stop	12.66	20.97	20.09	8.12	0.458	Medium Plastic& Inactive
4	Madithorai	14.74	22.36	30.3	7.94	0.378	Medium Plastic& Inactive

Scanning Electron Microscope (SEM)

A **Scanning Electron Microscope (SEM)** is a powerful imaging tool that generates high- resolution images by scanning a sample's surface with a **focused beam of electrons**.

These electrons interact with atoms in the sample, producing signals that reveal information about its **surface topography** and **composition**. The SEM operates by scanning the electron beam in a **raster pattern**, collecting emitted signals to construct a detailed image. **SEM can achieve resolutions finer than 1 nanometer**, making it essential for microscopic material analysis.

The **most common imaging mode** in SEM is the detection of **secondary electrons**, which are emitted when atoms in the sample are excited by the electron beam. The intensity of these emitted electrons depends on the **specimen's**

topography, allowing SEM to generate detailed surface images.

QuickGrid

Oasys Slope: 2D Slope Stability Analysis Oasys Slope is a powerful software tool for **two-dimensional slope stability analysis**, providing a user-friendly platform to assess various slope stability problems efficiently. It allows users to analyze **reinforcement elements** such as **soil nails, rock bolts, ground anchors, and geotextiles**. The software evaluates **slip surfaces**, determines the **factor of safety** against failure, and assesses the effect of reinforcements.
The program employs the **method of slices** to perform slope stability analysis and presents results in a **clear graphical format**. It also supports the application of **partial factors**, including **Eurocode 7 (EC7)**. Oasys Slope is primarily designed for slope stability analysis but can also be used for **earth pressure and bearing capacity assessments**. The software accommodates **both circular and non- circular failure surfaces**, making it applicable to both **soil and rock slopes**.

Key Features of Oasys Slope

Multiple Analysis Methods:

Swedish Circle (Fellenius)
Method
Bishop's Method
Janbu's Method

Failure Surface Analysis:

Supports **circular** and **non- circular** slip surfaces.
Circular slip surfaces can be defined using a **rectangular grid of centers**, a **common point**, or a **tangential surface**.
Non-circular slip surfaces are specified using **x and y coordinates**.

Soil and Groundwater Modeling:

Ground stratification is specified using **x and y coordinates** for each layer.
Soil properties are defined using **cohesion (c')** and **shear resistance angle (φ')**, with the option for **linear cohesion variation with depth**.
Individual groundwater profiles and **pore water pressure distribution** can be assigned per soil stratum.

Reinforcement & External Loading:

Supports various reinforcements, including **geotextiles, soil nails, rock bolts, and ground anchors**.
Reinforcement calculations follow **BS8006:1995** standards.
Allows **submerged and partially submerged slope analysis**.
Can include **external forces** (e.g., building loads or excavation strut forces).
Supports **earthquake loading** through horizontal acceleration of the slip mass.

Factor of Safety Calculation:

Determines the **factor of safety (F)** as the **ratio of restoring moment to disturbing moment**.
Uses iterative calculations, converging when the difference between two successive values is within tolerance.

Variably Inclined Interslice Forces

The **variably inclined method** ensures **horizontal and vertical equilibrium** for each slice while maintaining overall slope stability. However, it does not check whether the **shear strength along the slice interface** is exceeded. To compensate, adjustments are applied iteratively based on **residual force values** from previous calculations.

Method of Analysis: Bishop's Method Bishop's Method (Bishop, 1955) is widely used for circular slip surface analysis. It is essential for analyzing reinforced slopes, offering three solution techniques:

Horizontal Interslice Forces
(Bishop's Simplified Method)

Parallel Interslice Forces (Spencer's Method)

Variably Inclined Interslice Forces

Bishop's Simplified Method – Horizontal Interslice Forces

Assumes **interslice shear forces sum to zero** (Xn - Xn+1 = 0).
Satisfies **vertical equilibrium** but not **horizontal equilibrium**, causing minor errors in **factor of safety calculations**.
Satisfies **overall moment equilibrium**, making it a reliable and conservative approach.

Bishop's Method – Parallel Inclined Interslice Forces (Spencer's Method)

Assumes all interslice forces are **parallel** but at a constant inclination (not necessarily horizontal).

Satisfies **horizontal, vertical, and moment equilibrium**, improving accuracy.
More accurate for **steep slopes**, as errors from the simplified method increase with slope angle.
May experience **interlock issues**, requiring the **variably inclined interslice forces method** as an alternative.

Bishop's Method – Variably Inclined Interslice Forces

Further refines Bishop's method to **eliminate interlock issues**.
Iteratively adjusts **interslice force inclinations** to satisfy **horizontal, vertical, and moment equilibrium**.

Input Data for Slope Analysis

To perform an analysis, the following **input data** is required:

- **Ground Surface Profile:** Coordinates defining the slope surface.
- **Soil and Rock Stratigraphy:**

Location of each subsurface layer.

- **Groundwater Data: Phreatic surface and pore pressure distribution**.
- **Piezometer Locations:** If groundwater monitoring data is available.
- **External Loads:** Applied forces, such as buildings or retaining walls.
- **Slip Surface Definition:**
  - Circular: Defined by **center coordinates and radius**.
  - Non-Circular: Defined by a **series of x and y coordinates**.
- **Material Properties**

Each soil type must be characterized using:

- **Unit Weight:** Bulk density above and below the water table.
- **Condition:**
  - **Undrained**
  - **Drained (linear strength)**
  - **Drained (power/hyperbolic function strength)**

Shear Strength Parameters

- **φ' (deg):** Angle of friction.
- **c':** Drained cohesion.
- **c_0:** Undrained shear strength at a reference elevation.
- **k:** Rate of increase in shear strength with depth.
- **cu/p':** Normalized undrained shear strength ratio.
- **a & b:** Constants used for advanced material modeling.

Partial Factors in Analysis

Partial factors adjust the influence of material properties, loads, and reinforcement strength based on **design standards**. The software provides **default partial factors** compliant with:

- **BS EN 1997-1:2011 (Eurocode 7)** –

Design Approach 1, Combinations 1
& 2

- **BS8006-1:2010 Sections 7 & 8 (ULS)**
- **BS8006-2:2011 Sets 1 & 2**

If no partial factor set is selected, the software defaults to **1.0 (no adjustment)**.
Partial factors can be applied to:

- Favorable/unfavorable loads
- Soil unit weight
- Cohesion (drained & undrained)
- Friction angle
- Restoring moment
- Reinforcement pullout strength

Groundwater Modeling

The pore water pressure distribution can be defined using:

- **Phreatic Surface with Hydrostatic Distribution**
- **Phreatic Surface with Piezometric Pressures** (from piezometers)
- **Ru Method** (Ratio of pore water pressure to total overburden pressure)

Water table locations can be defined via **graphical input or imported DXF files**. **Slip Surface Definition**
Slip surfaces in Oasys Slope can be categorized into two types: **circular** and **non- circular** profiles.

Circular Slip Surfaces

A circular slip surface is determined by the **x and y coordinates** of its center and its **radius**. The center can be defined either as a **single point** or as part of a **grid of potential failure surface centers**.

Non-Circular Slip Surfaces

If a **non-circular** slip surface type is selected in the **General Parameters** dialog box, the **Data Slip Surfaces** option provides a table where users can input **x and y coordinates** to define the non-circular slip surface.
Graphical Input: Achanakal

9. CONCLUSION

The experimental and software analysis of soil samples from landslide-affected areas has provided critical insights into slope stability, failure mechanisms, chemical composition influences, and the impact of rainfall. Based on these findings, site-specific remedial measures have been proposed to mitigate risks and enhance slope stability.

9.1 Site-Specific Remedial Measures

Achanakal

The slope at Achanakal is relatively steep, and landslides have occurred primarily during the rainy season. Excessive runoff, high infiltration rates, and increased pore pressure have contributed to slope failure. The factor of safety analysis indicates that the location is highly unstable under both wet and dry conditions, with an increased risk of failure even with minor rainfall.

Recommended solution:

Construction of retaining walls with drainage pipes to achieve the minimum required factor of safety and prevent sliding.

Marapalam

This slope was cut to construct roads along the hilly region, leading to instability. Heavy rainfall has triggered landslides, causing severe damage and blocking three bridges. The primary cause of failure is the removal of natural slope support due to slope cutting.

Recommended solution:

Soil reinforcements, including **rock bolting** and **soil anchors**, to stabilize the rocky layer since the soil has already been eroded.

Gandhinagar Bus Stop

This slope, though smaller, is steeper due to land cutting and encroachments. It is at high risk of landslides throughout the year due to both external loads and rainfall. The abrupt change in terrain, combined with its location at a major bus stop, poses significant hazards to property and accessibility.

Recommended solution:

- **Construction of retaining walls with weep holes** to provide stability while allowing proper drainage.
- **Gabion walls** may also be used to enhance slope stability.

Madithorai

This landslide site is along State Highway SH-15 (Ooty-Kotagiri Road) and is one of the largest landslides recorded in the Nilgiri district. The primary causes of failure include high pore pressure, crown cutting, and slope excavation for road construction. The lack of proper retaining structures has further aggravated instability.

Recommended solution:

- **Soil reinforcements**, such as **soil nails, soil anchors, and embankments reinforced with geo-membranes and geo-textiles**, to enhance slope stability and prevent further sliding, especially during heavy rainfall.