# CASE STUDY AND FORENSIC INVESTIGATION OF LANDSLIDE AT MARDOL IN GOA

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**Keywords:** Forensic Investigations, Landslides, Slope Failure

**Abstract**:

Goa, like the rest of India is undergoing an infrastructure boom. Many infrastructure works are carried out on hill sides in Goa. As a result there is a lot of hill cutting activity going on in Goa. This has caused major landslides in many parts of Goa leading to damage and loss of property and the environment. Forensic analysis of a failure can significantly reduce chances of future slides. The primary purpose of post failure slope and stability analysis is to contribute to the safe and economic planning for disaster aversion. Western Ghats (also known as Sahyadri) is a mountain range that runs along the west coast of India. Most of Goa's soil cover is made up of laterites rich in ferric-aluminium oxides and reddish in colour. Although such laterite composition exhibit good shear strength properties, hills composing of soil possessing low shear strength are also found at some parts of the state. The shear strength parameters of slope material along with slope face, slope angle and height play an important role in governing the stability of a slope. The pore pressure conditions of the slope is also a critical factor. A complete understanding of the nature and causes of slope failures requires a complete investigation into various factors affecting the soil and the slope at the site under consideration. The shear strength parameters of the soils need to be determined using tests. Based on them the forensic study of stability of the slope was determined. The present paper is a forensic analysis of one such landslide occurred alongNH-4A at Mardol, PondaGoa. The landslide is suspected to have occurred due to increase in weight of the sliding soil mass after the area having recently experienced a heavy rainfall. A detailed investigation has been carried out to understand various aspects of failure and possible stabilization techniques to avoid such landslides in future.

## INTRODUCTION

The term landslide is used to describe a wide variety of processes that result in the downward and outward movement of slope forming materials composed of rocks, soils, artificial fill or a combination of these (Boop,1991). The material may fall by toppling, sliding, spreading or flowing. Goa has more than 50% of its area under hilly mountainous terrain namely the Sahyadris range and the foothills. These are very old and stable formations compared to the recently formed Himalayas. They face threat due to rapid development and hill cutting for various purposes including infrastructure and mining.

The common sight of relief, swathes of verdant forest, raging fast flowing rivers and rivulets, steep slope and so on characterize the mountain ecosystem of the state of Goa. On the west coast of India, west and north-west slope facets receive maximum rainfall, and are therefore more vulnerable to failure. Considering the fragility, diversity and complexity of the existing geo-environmental setting and the ecosystem, manipulation of natural constant either by nature or man in an unsustainable manner can lead to an irreparable short as well as long term negative side effects and devastation. Forensic analysis of a failure can significantly improve chances of future success.

In most cases the triggering factors are invariably buildup of pore water pressure due to excessive water during monsoons. Landslides triggered by heavy rain have been constant sources of destruction of property and loss of lives. Dormant as well as active slides are a threat to human life and property. Their study and monitoring has become imperative to safeguard against destruction by them. Developmental activities to be sustainable must be confined away from landslides prone and landslide affected locations. So far, disasters caused by landslides, earthquake, flood etc. have not led to large scale human tragedy in Goa in recent memory. However, there is ever increasing human demand of natural resources, especially land for urban development and infrastructure works thereby diverting the attention towards exploring the hills of Goa. The emerging crisis can be minimized by indigenous knowledge based and modern technological interventions prior to start of any construction work.

A landslide occurred in the village of Mardol, in south Goa district at the foot of a hill adjacent to NH4A highway. The proximity of the site to a highway caused a concern and hence was the motivation behind this study. This paper presents a forensic analysis of the landslide at Mardol, Goa. Figure 1(a) shows a google earth image of the location of the site and a photograph taken at the site is shown in Figure 1(b). A forensic investigation of the site includes the following:-

- Google earth image showing location of site.
- Site Survey
- Soil samples
- Stability analysis
- Suggested mitigation measures


(a) (b)

**Figure 1: (a) Location of site, (b) Landslide at site.**

## LANDSLIDE TYPES AND CLASSIFICATION

Various Engineering disciplines have developed classification system to describe natural phenomena. These systems are based on specific repeatable characteristics. In landslide classification, there are great difficulties due to the fact that phenomena are not perfectly repeatable; usually being characterized by different causes, movements and morphology, and involving genetically different materials. For this reason, landslide classifications are based on different discriminating factors, sometimes very subjective. The following table (Table1) shows a schematic landslide classification, which is based on movement type and material of the slope.

**Table 1 Types of land slides**

| Movement type | | | Material type | | |
|---|---|---|---|---|---|
| | | | Bedrock | Soil type | |
| | | | | Fine | Coarse |
| Fall | | | Rock fall | Earth fall | Debris fall |
| Topples | | | Rock topple | Earth topple | Debris topple |
| Slides | Rotational | | Rock slump | Earth slump | Debris slump |
| | Translational | Few units | Earth block slide | Earth block slide | Debris block slide |
| | | Many units | Rock slide | Earth slide | Debris slide |
| Lateral spreads | | | Rock spread | Earth spread | Debris spread |
| Flows | | | Rock flow | Earth flow | Debris flow |
| | | | Rock avalanche | | Debris avalanche |
| | | | Deep creep | Soil creep | |
| Complex and compound | | | Combination in time and /or space of two or more principal types of movements | | |

## FACTORS AFFECTING LANDSLIDES

The mountain slope are governed by laws of gravity and with the forces of lubricant like soil and the resistance to motion. The factors affecting these motions can be broadly divided into two groups:

(A) The first one is made up of the criteria utilized in the most widespread classification systems that can generally be easily determined. These are called as the Deterministic Factors.

(B) The second one is formed by those factors that have been utilized in some classifications and can be useful in description only. These are called as the Descriptive Factors.

### Types of movement

This is the most important criteria. As the mechanisms of some landslides are often particularly complex, uncertainties and difficulties can arise in the identification of movements. The main movements are falls, slides and flows, but usually topples, lateral spreading and complex movements are added to these.

### Material Involved

Rock, earth and debris are the terms generally used to distinguish the material involved in the landslide process. The distinction between earth and debris is usually made by comparing the percentage of coarse grain size fraction. If the weight of the particles with a diameter greater than 2mm is less than 20%, the material will be defined as earth; in the opposite case, it is debris.

### Activity

The classification of a landslide based on its activity is particularly relevant in the evaluation of future events. The concept of activity is defined with reference to the spatial and temporal conditions, defining the state, the distribution and the style. The first term describes the information regarding the time in which the movement took place, permitting information to be available on the future evolution, the second term describes, in a general way, where the landslide is moving and the third term indicates how it is moving.

### Type of climate

These criteria give particular importance in the genesis of phenomena for which similar geological condition can, in different climatic conditions, lead to totally different morphological evolution. As a consequence, in the description of a landslide, it can be interesting to understand in what type of climate the event occurred.

## CAUSE OF LANDSLIDES

The mountain slope are governed by laws of gravity and with the forces of lubricant like water, unstable slope-forming material shall continue to move downwards and cause economic loss in terms of life and property. The landslide trigger mechanism is shown in Figure 2. Landslide with heavy rainfall causes flash floods in the valleys. Landslides or mass movement phenomena in a mountainous state can be attributed to the following causative factors solely or in combination with:

1. Geology of the area.
2. Rainfall.
3. Slope angle and slope formation materials.
4. Hydrological condition of the area

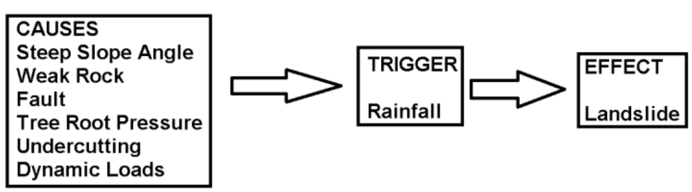


**Figure 2: landslide trigger mechanism**

Causes may be considered to be the overall factors that made the slope vulnerable to failure, that predispose the slope to becoming unstable whereas, trigger is the single event that finally initiate the landslide. Thus, causes combine to make a slope vulnerable to failure, whilst the trigger finally initiates the movement. Usually, it is relatively easy to determine the trigger after the landslide has occurred (although it is generally very difficult to determine the exact nature of landslide triggers ahead of a movement event). The various causes of landslides are listed as follows:

1. Geological Factors

These include materials which are weak, sensitive, weathered, sheared, jointed or fissured and with adversely oriented discontinuities. The materials also show a wide contrast w.r.t. permeability.

2. Morphological causes

These include slope angle, uplift rebound, fluvial erosion, wave erosion, glacial erosion, erosion of lateral margins, subterranean erosion, slope loading, vegetation change.

3. Physical causes
   Intense rainfall, rapid snow melt, prolonged precipitation, rapid drawdown, earthquake, volcanic eruption, thawing, freeze-thaw cycle, shrink-swell, ground water changes and other mass movements are some of the physical causes of landslides.
4. Human causes
   Human activities like excavation, loading, drawdown, change in use of land, water management, mining, quarrying, vibration and water leakage also add to the possibilities of landslide.

## RAINFALL AS A TRIGGER

Considerable efforts have been made to understand the triggers for land sliding in natural sytems, with quite variable results. In the majority of cases, the main trigger of landslides is heavy or prolonged rainfall. Generally, this takes the form of either an exceptional short lived event, such as the passage of a tropical cyclone or even the rainfall associated with a particularly intense thunderstorm or of a long duration rainfall event with lower intensity, such as the cumulative effect of monsoon rainfall in South Asia. This is explained in Figure 3.

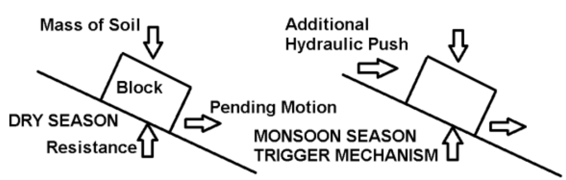


**Figure 3:Rainfall as trigger**

In the former case, it is usually necessary to have very high rainfall intensities, whereas in the latter the intensity of rainfall may be only moderate- it is the duration and existing pore water pressure conditions that are important. The importance of rainfall as a trigger for landslides cannot be under-estimated. Almost all the landslides in Goa occur after prolonged exposure to monsoon rains and occasionally during or just after cloudburst or precipitation intensity exceeding 135-145 mm in 24 hours. They usually start occurring after August when the soils are fully saturated by the June - July rains.

The Figure 3 illustrates the forces acting on an unstable block on a slope. Movement is driven by shear stress, which is generated by the mass of the block acting under gravity down the slope. Resistance to movement is the result of the normal load. When the slope fills with water, the fluid pressure provides the block with buoyancy, reducing the resistance to movement. In addition for some cases, fluid pressures can act down the slope as a result of groundwater flow to provide a hydraulic push to the landslide that further decreases the stability. In some situations, the presence of high levels of fluid may destabilize the slope through other mechanism, such as:

• Fluidization of debris from earlier events to form debris flows.

• Loss of suction forces in silty materials, leading to generally shallow failures (this may be an important mechanism in residual soils in tropical areas following deforestation).

• Undercutting of the toe of the slope through river erosion or for construction works.

## FORENSIC INVESTIGATION TECHNIQUES

The primary purpose of post failure slope and stability analysis is to contribute to the safety of slopes. Proper forensic investigation needs to be carried out using Non Destructive Techniques. The other techniques used are, still-photography, scale object in photograph, land surveying, visual inspection and soil sample followed by lab testing and stability analysis with the aid of slope stability softwares.

### Site Conditions

Site conditions play an important part in stability and failure of slope. Slope face and slope angle and height play an important role in governing the stability of slopes. As they increase, chances of failure also increase. The degree of saturation of the slope material is also a major factor. The soil at site was poorly graded clayey sand. Patches of yellowish clayey-sand layers were observed. As the landslide was fresh, the soil was moist and lumps of it could be easily squeezed in hand. Figure 4(a) shows the yellowish clayey sandy layer and Figure 4(b) shows the failure of slope.


(a) (b)

**Figure 4: (a) Photo showing yellowish clayey sandy layer, (b) Photo showing failure of slope.**

## FIELD INVESTIGATIONS

Field investigations have been carried out as per template provided by national Disaster Management Authority (NDMA 2015). A deeper understanding of the nature and causes of these failures requires a detailed investigation into the geology, groundwater conditions, geotechnical characteristics, topography, seismicity and weather patterns at the site under consideration. The shear strength parameters of the soils need to be determined using tests. Based on them the forensic study of stability of the slope was carried out.

### Topographical Maps

As the entire area was almost clear of any obstruction a theodolite survey was carried out to locate the significant points and the slope of the ground. The sectional maps were prepared using these. The section is shown in Figure 5.

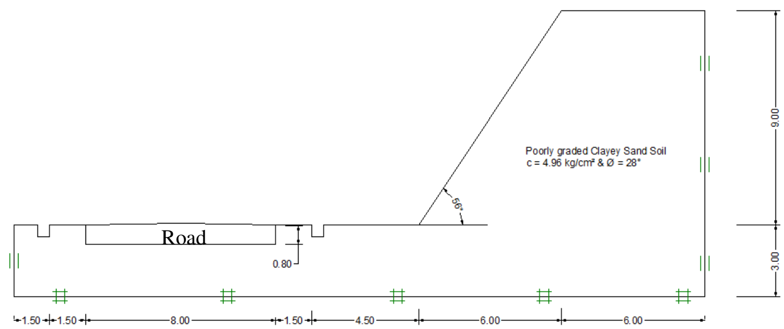


**Figure 5 : Section of site (dimensions in meters).**

### Geomorphology

The site is a hill cutting 9 m high for roadworks as shown. It is west facing and a considerable reduction in vegetation cover on top of slope is seen at location where the landslide has occured.

### Metrology

On the west coast of India, in the western ghats region, the west and north-west slope facets receive maximum rainfall, and are therefore more vulnerable to failure. This site being on the west is no exception in facing heavy rainfall. Heavy rains impact the region from June to October. By mid July soil is fully saturated and hence most failures and landslides occur in this season.

### Regional Geology

The soil is basically formed of thin layers of red clayey sand interspersed with thick layers of yellowish clayey soil both of which have very weak shear strength. Figure 6, shows the photos resembling regional geology.

**Figure 6: photograph of soil layers resembling regional geology.**

## LABORATORY INVESTIGATIONS

Soil samples were collected and standards laid down in relevant IS codes have been followed for sampling and testing of soil. The values found were used for stability analysis.(4)

### Soil Samples

Soil samples were collected from different locations at site. These were kept safe and dry in polyethelene bags in the soil-mechanics laboratory of the Department of Civil Engineering, Goa Engineering College and marked, indicating the soil description, sampling depth and date of sampling. Classification test (natural moisture content, specific gravity, Grain size analysis and Atterberg's limits,) and compaction test (optimum moisture content, Maximum Dry Density)were performed on the samples to determine the geotechnical properties of the samples. The average values have been presented below in Table 2.

**Table 2: General Soil Properties**

| Specific Gravity | Moisture Content | Compaction Test | | Atterberg Limits | | |
|---|---|---|---|---|---|---|
| | | OMC % | MDD g/cc | Liquid limit WL % | Plastic limit wP % | Plasticity index IP % |
| 2.47 | 22.9 | 12.13 | 1.83 | 27 | 11.7 | 15.3 |

### Soil Shear Strength Parameters

Engineering property test for shear strength were performed on the samples A, B and C and the values are indicated in Table 3.

**Table 3: Shear Strength Parameters of Soil**

| c | Ø |
|---|---|
| 4.96 $kg/cm^2$ | $28^{\circ}$ |

## STABILITY ANALYSIS

Terzaghi describes failure causes as "internal" and "external" referring to modification in the conditions of the stability of the bodies. Whilst the internal modifications in the material itself which decreases its resistance to shear stress, the external causes generally induce an increase of shear stress, so that block or bodies are no longer stable. It should be noted that the triggering causes induce the movement of the mass. Predisposition to movement due to control factors is determining in landslide evolution. Structural and geological factors, as already described, can determine the development of the movement, inducing the presence of mass in kinematic freedom.

The Bishop's method of slices is used when the slope consists of different soil layers with varying c and Ø values. The soil mass above the failure surface is divided into number of slices and the forces acting on each slice is determined from limit equilibrium method. The equilibrium of the entire mass is determined by summing the forces of individual slices.

**Failure Analysis and Results**

The current landslide slope site is analysed with a software OptumCEG2 which a finite element program dedicated to geotechnical deformation and stability analysis. The analysis was carried out by limit analysis and considering linear elastic materials of Mohr- Coulomb type. Limit analysis and strength reduction methods were used to get a graphical failure pattern and factor of safety as the output. In limit analysis the fixed loads are kept constant gravity is amplified till failure occurs. The strength Reduction analysis proceeds by computing a strength reduction factor by which the material parameters need to be reduced in order to attain a state of incipient collapse. This reduction factor is taken as the factor of safety [Aniket R. Dessai and Nisha P. Naik, 2016]. The slope was analysed by dividing it into 1000 number of elements. Figure 7 shows the slope model in software. The slope at present condition is having factor of safety of 0.45 which implies that the slope is just stable with present conditions and is highly susceptible to failure with any further loading or increase in pore pressure. Figure 8 shows the software result of slope failure. It is a slip circle failure and this could also be depicted from the site photographs.

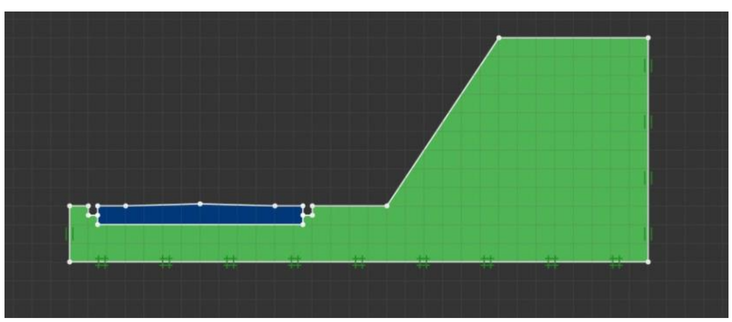

**Figure 7 : Model of the slope adopted for analysis**

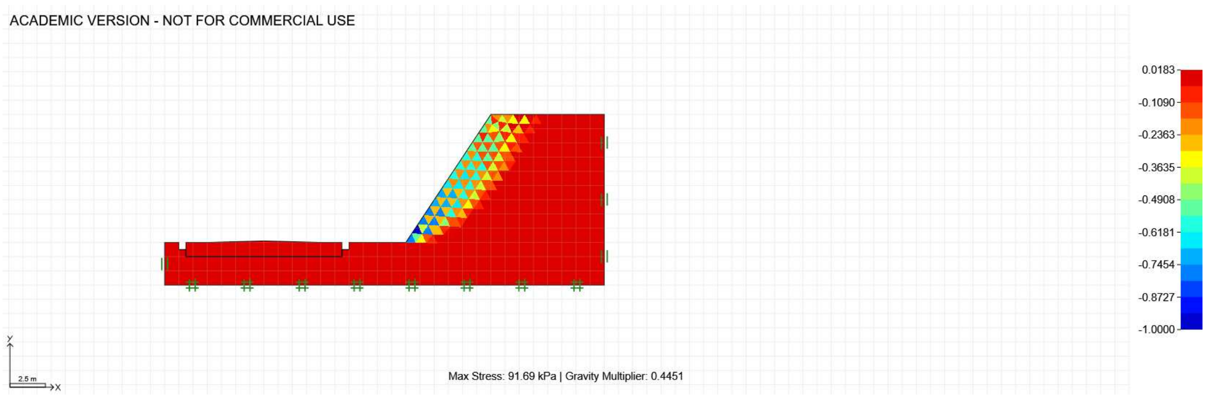


**Figure 8 : Slope failure (F.O.S = 0.45)**

## Cause of this Landslide

As known from stability analysis that the slope is highly vulnerable to further loading or increase of pore pressure, the only possible cause for this landslide can be the continuous heavy rainfall experienced in this region during monsoons. The destruction of natural vegetation along this area has also added to its instability. The slope must have been saturated during rains and thereby increasing its self-weight and eventually leading to collapse.

## MITIGATION MEASURES

The purpose of the landslide mitigation is to stop or reduce the landslide movement so that the resulting damages can be minimized (Singh et al 2015). The approaches for mitigating landslide may include:

1. Restrictions of development in landslide prone areas,
2. Modification in geometry of slope, grading, landscaping,
3. Landslide mitigation works, and
4. Warning systems

## Benching

Benching results in modification in the geometry of the slope and also decreasing the weight of the earth retained slope. It also helps in decreasing storm water flow and prevent erosion of soil. Figure 9 shows the benching of mardol slope with approx. 1:1 cutting. However in the analysis a horizontal cut of 4.00 meters is taken for a height of 4.50 meters.

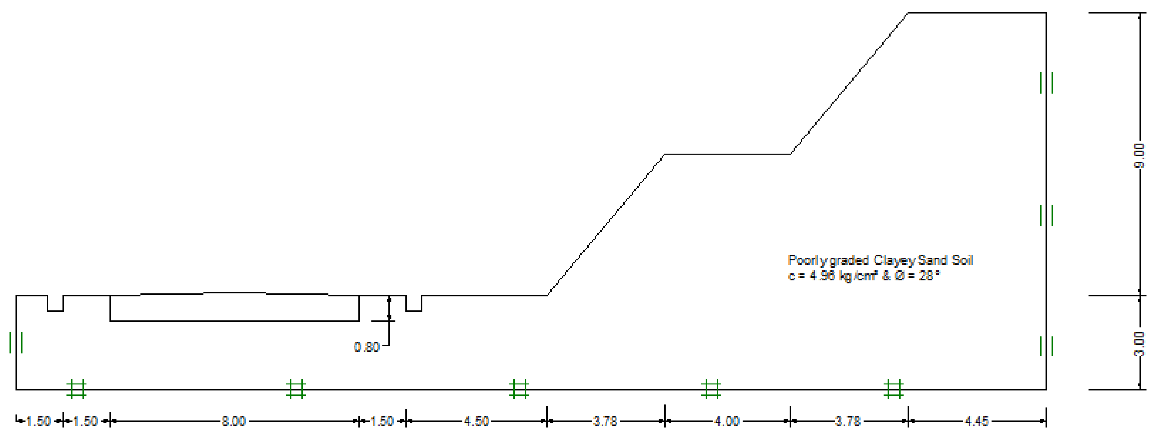


**Figure. 9: Proposed benching for Mardol slope (dimensions in meters).**

The current analysis of this slope after benching gave a factor of safety of 1.09 which is 42% more than that without benching. The stability result is shown in Figure 10.

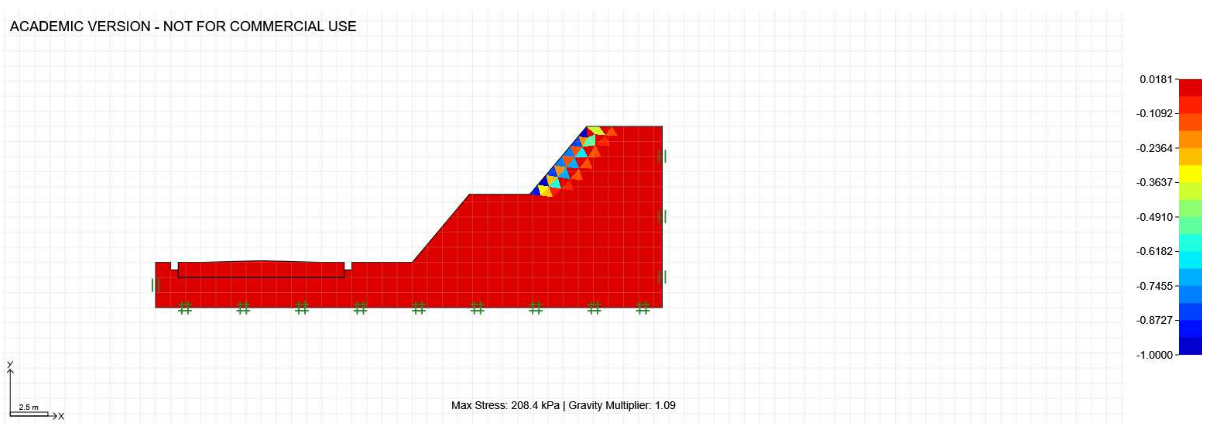


**Figure 10: Stability of slope after benching ( F.O.S= 1.09)**

**Installation of nails on unstable hillside**

Reinforcement measures generally consist of the introduction of metal elements to increase the shear strength of the rock. As far as the working mechanical of a rock nail is concerned, the strains of the rock induce a stress state is the nail composed of shear and traction stress, due to the roughness of the joint, to their opening and to the direction of the nail, generally non-orthogonal to the joint itself. Soil nailing is providing passive reinforcement of existing ground by installing closely spaced nails i.e. steel bars of required diameter. The nails are then fixed on surface with bearing plate and later if required covered with shotcreting.

The soil nailing for Mardol slope with steel bars of 8.50 meters length and axial strength of 500KN/m with bearing plates of size 280x280x20mm gave a factor of safety of 1.06 (almost same as that obtained on benching). Figure 11 shows the soil nailing section of slope. The stability analysis is shown in Figure 12.

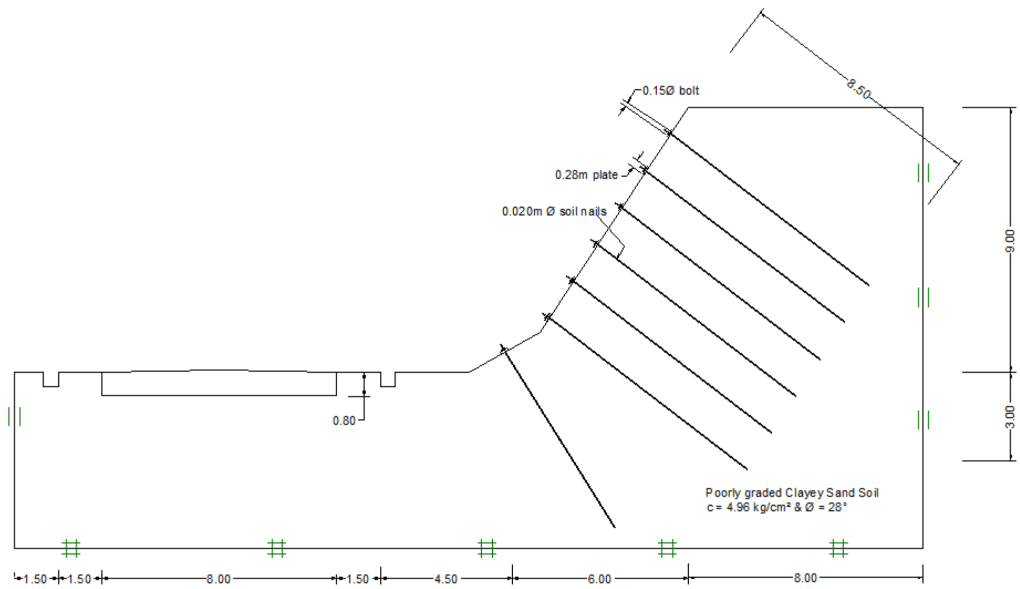


**Figure 11: Slope cross-section showing soil nails (dimensions in meters).**

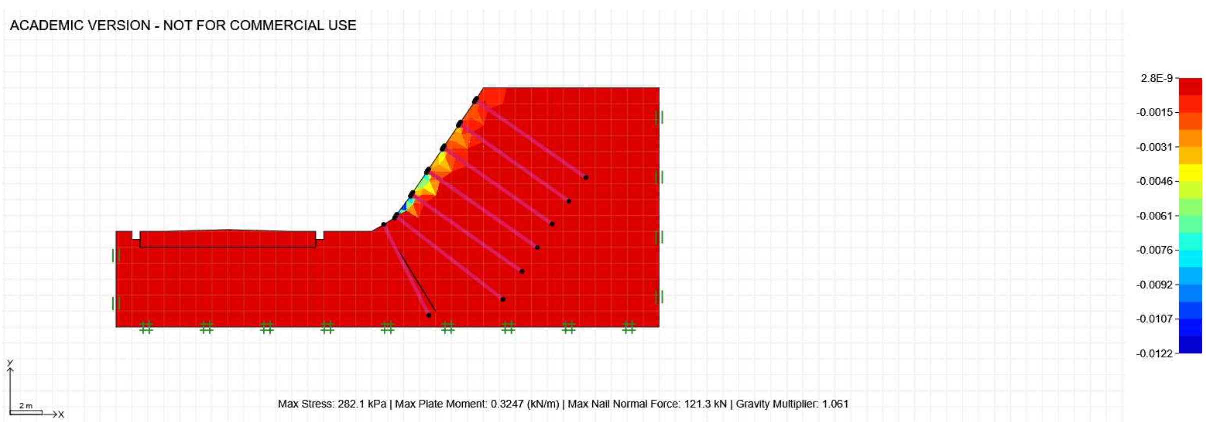


**Figure 12: Stability analysis of soil nailed slope**

## OTHER MITIGATION MEASURES INCLUDE:

### Installation of anchors

Anchorage can be classified as active anchorage, in the case in which they are subjected to pre-tensioning, and passive anchorage. Passive anchorage can be used both to nail single unstable blocks and to reinforce large portions of rock. It is, therefore, a specific type of anchorage, not structurally connected to the free length, made up of an element resistant to traction, normally a steel bar of less than 12m, protected against corrosion by a concrete health.

## Drainage

The presence of water within a hillside is one of the major factors leading to instability. This can be avoided by;

- Preventing water entering the hillside through open or discontinuity traction cracks.
- Reducing water pressure in the vicinity of potential breakage surfaces through selective shallow and sub-shallow drainage
- Placing drainage in order to reduce water pressure in the immediate vicinity of the hillside.

### Vertical Drainage

Vertical drainage is generally associated with sunken pumps which have the task of draining the water and lowering the groundwater level.

## Growing Vegetation

Vegetation growth has always been a good method of stabilizing slopes as the trees prevent soil erosion by creating a dense network of roots within. Moreover growing trees is also a sustainable approach towards slope stability. Vetiver grass is a tall, tufted, perennial, scented grass, with a straight stem, long narrow leaves and a lacework root system that is abundant, complex, and extensive. It offers an inexpensive yet effective and eco-friendly tool to combat soil erosion. Vetiver, with its many advantages and very few disadvantages, is a very effective, economical, community-based and environmentally-friendly sustainable bioengineering tool that protects infrastructure and mitigates natural disasters [C. Ghosh]

## CONCLUSIONS

More than 50% of the land of Goa comprises of hill regions. Some are strong due to oxidation of rocks while some are weak due to poor geological formations. The hilly region in vicinity of Mardol area comprises of weak clayey sandy soil. Analysis showed us that the slopes in this area are marginally stable with F.O.S of 0.45 and highly susceptible to failure during monsoons or on loading. The stability of current slope was seen to increase by 42% i.e. F.O.S of 1.09 by adopting benching and by 35% i.e. F.O.S of 1.06 on soil nailing. Apart from this other mitigation measures like slope flattening, vegetation cover using Vetiver grass are proposed as they are seen to increase the stability of slopes.

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