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Probabilistic analysis of slope stability in Soils and Soft Rocks

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Abstract – Slope stability poses serious problems in Costa Rica due to its geographical position and geological characteristics. It is important for geotechnical engineers and designers to use analysis methods which are accurate and reliable when analyzing slope stability. The combination of deterministic and probabilistic methods provides more precise and reliable results. The present study evaluates the stability under four different conditions of two slopes, located at km 17 and km 29 of a national highway, between San Ramón and Quesada, in Costa Rica. A probabilistic method is used to estimate not only the safety factor, but the probability of failure, in order to come up with a safer and more rational slope design for this road section.

***Keywords*: **Deterministic method, probabilistic method, probability of failure, slope stability.

1. Introduction

Because of the geographical and geological conditions of Costa Rica, many roads and road construction projects pose serious problems related to slope stability. These problems can be minimized if adequate and more precise geotechnical analysis is performed. In order to find appropriate solutions to geotechnical problems and analysis, many studies using deterministic and probabilistic methods have been carried out in tropical and subtropical areas. These studies have provided better ways to characterize the soils in these regions, as an alternative to the traditional methods for characterizing and evaluating soils, thus allowing geotechnical engineers and designers to come up with more rational and reliable technical decisions.

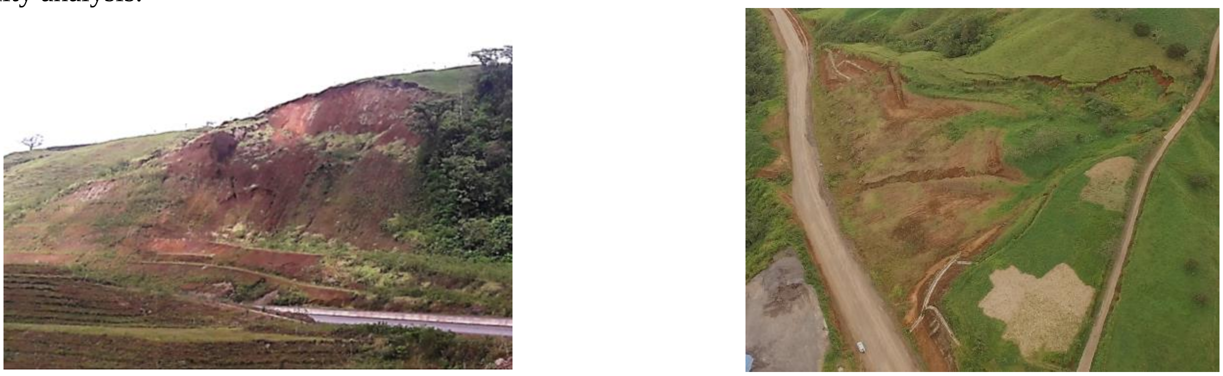
Traditionally, deterministic mathematical analysis have been used to determine slope stability by using a factor of safety. This type of model takes into account factors that affect slope stability, such as slope geometry, geological parameters, seismic loads, water flow, soil properties, etc. Recently probabilistic methods have proven to be very useful and accurate when assessing slope stability.

In this paper, a comparison is made of factors of safety obtained from using deterministic analysis (Morgenstern-Price method) and probabilistic analysis (Monte Carlo simulation). The results of the analysis were used to determine cut slope stability. The probabilistic method was used to estimate, not only the factor of safety, but also the probability of failure for a given trust factor, as a way to ensure safe slope designs.

2. Methods

The area under study is located in the central mountain range in Costa Rica, which is a tropical country. This range is representative of the region geology. It is characterized by large slopes, significant soil thickness, and highly weathered soft rocks. The project area is susceptible to landslides due to the combination of different factors, such as effusive sedimentary geology, weathering, steep topography, seismicity, and severe rainfall. Studies in similar areas have been carried out [1],[2],[3],[4].

Two cut slopes were selected along a road construction project comprising a national highway sections between two cities, San Ramón and Ciudad Quesada. Figure 1 shows the slopes located at km 17 and km 29, which were selected, among other reasons, because of their accessibility. The SLOPE/W module from GeoStudio 2018 was used to perform the stability analysis.



A. Slope on km 17 B. Slope on km 29

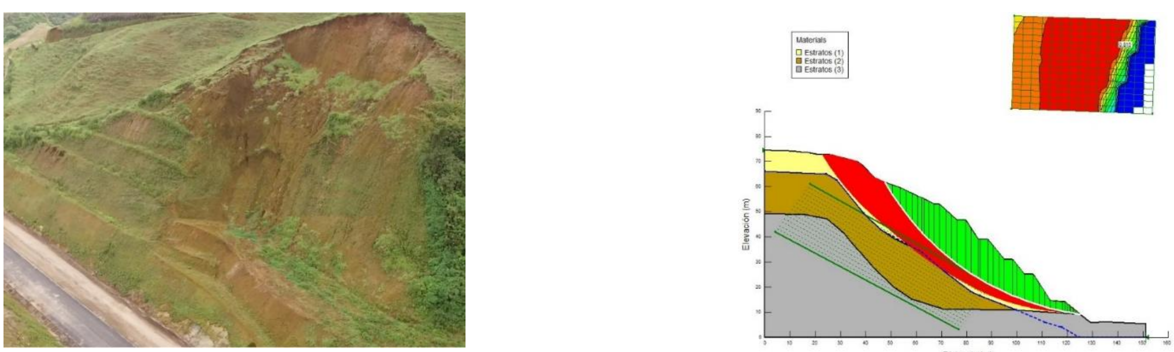
Fig. 1: Slopes under study.

The study comprised different stages, which can be summarized as follows:

1. Preliminary study: Data collection from previous records and reports, literature review, on-site visits, quick slope assessment, and selection of slopes to be studied.
2. Detailed study: Topographical survey, sample collection, characterization of physical mechanical properties of the soil layers and soft rocks, and testing for shear strength.
3. Modelling and calibration of the geotechnical model: Slope modelling in multiple scenarios (prior to construction work, under cutting/intervention conditions, under failure conditions, and using geometric slope correction), model calibration using different techniques, application of deterministic and probabilistic methods using GeoStudio 2018.
4. Analysis of results: Geometric correction of the design solution for the slopes under study.

Also, the influence of the soil shear strength obtained by consolidated-drained, consolidated-undrained, and unconsolidated-undrained testing was considered.

Figure 2 shows the cut generated with the road intervention, and the resulting landslide, as well as the model obtained.



A. Intervention and failure, slope at km 17. B. SLOPE/W output of slope failure after intervention, slope at km 17.

Fig. 2: Slope at km 17 after intervention and failure.

3. Results

In this paper, the results of the analysis performed on the slope located at km 17 are commented. Although the results for slope at km 29 were quite similar.

After modelling the slopes in four different scenarios (before construction work, under cutting conditions, under failure failure conditions and using geometric correction) a deterministic analysis for critical conditions was performed. With this this analysis, factors of safety greater than 1 were obtained. The obtained factors met the criteria specified by Costa Rica's Rica's geotechnical code for slopes and hillsides [5]. By means of probabilistic analysis, it was confirmed the fact that the probability of failure for both slopes after cutting the natural slope was higher than permissible by the standards, regardless of the obtained factor of safety. In all cases, the input data of the soil property were obtained by statistically processing the results of shear strength testing. The number of tests for each layer ranged from six to nine.

Probabilistic methods were used to validate a geometric correction because these methods guarantee a lower probability of failure, thus ensuring safety.

3. 1. Model before intervention (slope 17+100)

Based on the deterministic analysis, the slope was considered stable because the factor of security meets the criteria specified by [5]. With the probabilistic method, both for static and pseudo-static cases, the factors of safety are greater than the minimum values specified by [5], and the probability of failure is practically null. Thus, the slope is considered to be stable in its initial condition (natural hillside), both from the static and the pseudo-static points of view.

3. 2. Model after intervention, without landslide (slope 17+100)

With the deterministic analysis, the factors of safety are greater than the limit equilibrium condition and the values specified by [5]. This result confirms the hypothesis put forward by the original designers of the slope. The probabilistic analysis, under the static condition, provides failure probability values less than 1 % for the unsaturated slope; however, for the saturated zone above the water table, a probability of failure greater than 1 % provides evidence for the real conditions of failure, that is, during prolonged rainy periods. In the pseudo-static case, the factor of safety is greater than 1, with a failure probability less than 1 %, thus the slope is considered stable.

3. 3. Model after landslide (slope 17+100)

Based on the deterministic analysis, the slope is stable because the factors of safety in all cases are greater than 1, as specified by [5]. The probabilistic analysis for static cases shows that the factors of safety meet the criteria specified by [5]; however, the probability of failure in the saturated zone above the water table is greater than 1 %, thus confirming that slides can occur any time under this condition.

3. 4. Model using the geometric correction (slope 17+100)

Table 1 shows that the geometric correction of the slope provides minimum factors of safety which meet the criteria specified by [5], thus the probability of failure is practically null.

Table 1: Factor of safety values for the geometric correction model using the probabilistic method.

Cases	**Testing**	**Obtained factor of safety**	**Acceptable factor of safety**	**Cond.**	**Obtained probability of failure**	**Acceptable probability of failure**	**Cond.**
Static, with water table	Consolidated-undrained	1,951	1,5	Stable	0,000	0,01	Stable
Static, no water table	Consolidated-undrained	2,325	1,5	Stable	0,000	0,01	Stable

Static, with water table, saturated	Layer 1: Consolidated-undrained Layers 2,3,4: Consolidated-drained	1,919	1,3	Stable	0,000	0,01	Stable
Static, no water table, saturated	Consolidated-undrained	2,215	1,3	Stable	0,000	0,01	Stable
Pseudo-static, no water table	Consolidated-undrained	1,405	1,1	Stable	0,000	0,01	Stable

By using the probabilistic method it was possible to confirm the hypothesis related to the probability of failure after the intervention of the slopes under study. Also, it was proved that deterministic method are reliable for this type of analysis.

4. Conclusions

When the geotechnical model considered combinations of strength properties like consolidated-drained and consolidated-undrained, the results obtained from the modelling and the results obtained from direct observation were similar. However, when consolidated-drained and unconsolidated-undrained conditions were analyzed there was no coincidence between the model and the real on-site situation.

It was determined that the probability of failure was higher when the slope is in the saturated condition. This result corroborates what have been observed in the region throughout the years: landslides usually occur during intense rainfall and/or prolonged rainy periods. This demonstrates the need to take waterproofing and drainage measures to improve the slope geotechnical behaviour.

In some cases, factors of safety greater than 1 were obtained, but with greater probability of failure than admissible, thus probabilistic methods offer more precise and reliable solutions than deterministic methods.

Both probabilistic and deterministic methods provide factors of safety; however, probabilistic methods also provide failure probability values, which aid designers and geotechnical engineers in making more rational technical decisions.

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