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Comparison of Analyses of an Active Slide in Tropical Soil by Two-Dimensional and Quasi-Three-Dimensional Methods

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Abstract. Slope stability analysis is one of the oldest fields of geotechnical engineering and it has been performed for many decades, but it is still an active research topic, both in academia and in practice. Geotechnical engineers frequently use back analysis of old and new slides to estimate the shear strength of soils involved in construction of retaining structures and slope reinforcing or redesigning projects. Nowadays various software based on the two-dimensional (2D) method of Slices are used on a routine basis to perform such type of analysis. Little or no attention is given to the three-dimensional (3D) features of the problem, usually because the 3D analysis is more time consuming, because 3D methods and software are not so widespread and proven as 2D ones and because the 2D factor of safety is perceived to be lower than the 3D factor of safety, thus conservative. However, that may not always be the case. In this paper, an active slide is analyzed by a 2D method of Slices and by two quasi-3D methods. The slide took place in tropical soils. The factors of safety obtained by each method are compared, showing a small difference amongst them.

Keywords. Slope stability, two-dimensional, quasi-three-dimensional, method of slices.

1. Introduction

The beginning of the modern concept of slope stability analysis may be traced back to the introduction of the method of slices by Fellenius or by the Bishop's simplified method in the 1950s [1]. The aid of personal computers allowed geotechnical engineers to perform reliable slope stability analysis quickly. However, the never-ending possibilities brought by nature and human structures keep the issue as an active research topic, both in academia and in practice.

Nowadays various software based on the two-dimensional (2D) method of Slices are used on a routine basis to perform such type of analysis. Little or no attention is given to the three-dimensional (3D) features of the problem, usually because the 3D analysis is more time consuming, because 3D methods and software are not so widespread and

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proven as 2D ones and because the 2D factor of safety (FS_{2D}) is perceived to be slightly lower than the 3D factor of safety (FS_{3D}), thus conservative. However, the supposed level of conservatism of 2D analysis is usually unknown.

The FS_{2D} of a spherical slip surface, for example, is lower than the FS_{3D}, mainly because it neglects the contribution of the lateral boundaries of the slip surface to the overall strength. However, in slip surfaces with more complex shapes that may not be the case [2].

Moreover, the FS_{2D} in a 3D problem will depend on the chosen section. It implies that a conservative result will be obtained only if the most pessimistic section of the 3D problem is chosen. In a slope that contains layering and strength and pore-pressure variability in the third dimension, this 'most pessimistic' section may not be obvious [2].

It is also common practice to compare shear strength estimated by back analysis to the one estimated by laboratory tests in order to obtain reliable parameters for design. However, that comparison may be difficult because the laboratory tests do not replicate several features of the field condition. Indeed, there is an unwanted consequence of a conservative 2D slope stability back analysis of a failed slope: it will lead to an unconservative overestimation of the soil shear strength [3]. That error may be canceled if the parameters obtained in the 2D back analysis are used in a 2D design method. Caution must be exercised, however, because if comparable 3D effects do not exist for structure to be designed, the results may be on the unsafe side [4].

In this paper, an active slide is analyzed by the a 2D method of Slices [5] and by two quasi-3D methods [6] and [7]. The slide affected tropical soils and has an unusual geometry. The factors of safety obtained by each method are compared, showing a small difference amongst them.

2. Case study: the Três Barras Gully and the slope instability

A brief description of the Três Barras Gully and its slope movements will be presented herein to allow the discussion of the slope stability analyses. More details can be found in [8]. The site is in a hilly domain in the city of Bananal, State of São Paulo, Brazil. In the southeast coast of Brazil, landslides in these materials may be triggered by fluctuations of the groundwater level, erosion of the foot of the hills and intense rainfalls [9] and [10].

The Três Barras site (0.15 km^2) has been eroded continuously for decades by the flow of artesian water in a saprolitic layer. Presently the toe erosion is the cause of two sliding processes that develop side by side in the surrounding hill (Figure 1). The two sliding soil masses are indicated as "A" and "B". An approximately circular crack, with an opening of several decimeters, can be seen in the upper limit of soil mass "A", indicating that the slide is active. A straight crack can be seen in the upper limit of "B".

Information about the slides was collected by SPT penetration tests and rotatory drills, field inspections, laboratory tests, inclinometer and topographic readings. "A" cuts the layers of saprolitic soil and has a centripetal movement in plan view indicated by the dashed arrows. "B" slides along the direction of the foliation in a mica-rich layer located at the boundary between the saprolitic soil and the intact rock. The inclination of this planar slip surface is approximately 30 degrees.

The rate of erosion that undermines "B" is greatest in the upstream part of the gully causing the displacements of this slide to be higher in that region, as indicated by the dashed arrows. The crack aperture observed in the field (straight crack) confirms this interpretation because it varies from a few centimeters in the left side to up to 3m in the right side. Figure 2 shows a closeup of an aerial photo of the "B" movement. The white contour shows the soil mass "B" and the black arrows show the displacements in the crack.

In the lower portions of the basin, at the foot of the landslides, water springs are present. Piezometers installed at the contact of the saprolitic soil with the fractured rock show artesian pressures at the foot of both sliding masses, in the bottom of the gully. These pressures are maximum where the tip of the piezometer is close to the fractures of the underlying rock.

Back analyses have shown that the movements only started after the erosion reached a critical depth, i.e. the gully erosion was the trigger of the slides.

Figure 3a shows the profile of the weathered banded gneiss exposed in a sampling pit. Figure 3b shows a detail of a mica-rich dark layer, along which the "B" slide took place.

3. Slope stability analyses: data and methods

The details of several slope stability analyses, field monitoring and laboratory investigation of the soil properties can be found in [8].

The stratigraphy was based on field inspection in the scarps and gully walls, standard penetration tests and rotatory drillings. The ground level was obtained by topographic survey. The slip surface geometry was obtained by careful analysis of the topographic survey of the cracks (entrance and exit of the slip surface) together with inclinometer readings and stratigraphic sections. The monitoring of a dozen piezometers during approximately four years led to the estimation of the pore pressures.

Two new quasi-three-dimensional analyses will be shown herein and compared to the original 2D analyses. The intention of these analyses is not to assess the shear strength of the soils involved but to enable a comparison of the factors of safety obtained by the different assumptions and methods. Since the objective is the comparison among the methods, no effort will be taken to obtain unitary values.

3.1. Soil properties

According to the inclinometer readings, field inspections and SPT borings, the slip surface cut across two materials: a lateritic sandy clay underlain by a saprolitic soil. The central portion of the slip surface run along the soil-rock contact. The soil properties were estimated by submerged direct shear testing. Since the slide is active and the displacements were significant, it was decided to use the post peak shear strength of the lateritic and the saprolitic soil. Table 1 shows the shear strength parameters of the soils.

3.2. Cross sections

Five parallel sections, approximately perpendicular to the straight crack and 10m apart from each other, were chosen. Figure 4 shows the five sections in the topographic chart, along with the location of the inclinometers (indicated by the code I-N) and piezometers (indicated by the code PZ-NN), where N is a number. It is worth noting that the piezometers were installed in the SPT borings. Figure 5 shows an orthographic projection of the five parallel sections.

Table 1. Shear strength and unit weight of the investigated soils used in the analyses.

Soil	c' (kPa)	ϕ' (°)	γ (kN/m³) Above W.T.	γ (kN/m³) Below W.T.
Lateritic soil (sandy clay)*	18	30	14.8	17.5
Saprolitic soil*	11	29	18.6	19.6
Soil-rock contact**	11	29	–	19.6

*Direct shear tests in undisturbed flooded specimens.
**Residual strength by ring shear tests.

Figure 1. Aerial photograph of the study area.

3.3. Two-dimensional method of analysis

The well-known Spencer's method [5] was used for the 2D analyses. Figure 6 shows the 2D slope stability analysis of section B3.

3.4. Quasi-three-dimensional method of analysis: Lambe & Whitman

The 2D method consider only the stresses in a single vertical cross section through the slope. The contributions of the other sections are disregarded. However, when the 3D effects may be important, [7] proposed to consider three parallel cross sections and compute a weighted average. The quasi-three-dimensional factor of safety is:

$$FS_{q3D} = \frac{\sum_{i=1}^{3}\left(FS_{2D,i} \cdot W_i\right)}{\sum_{i=1}^{3} W_i} \quad (1)$$

where $FS_{2D,i}$ is the factor of safety for the ith 2D cross section and W_i is the total weight above failure surface in the ith cross section and is the weighting factor in the weighted average.

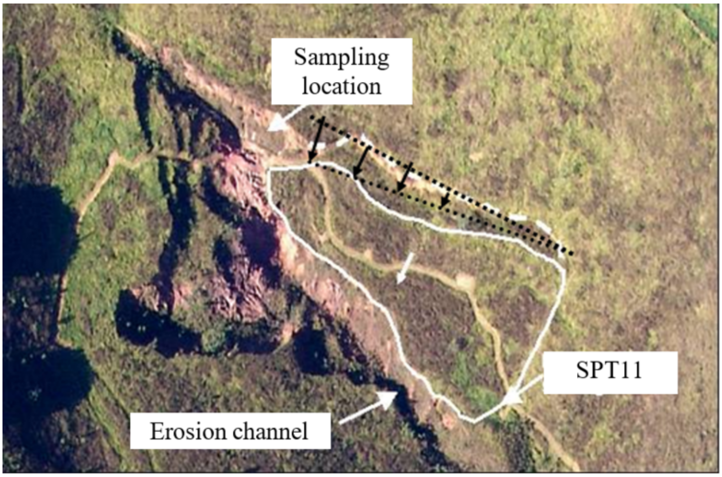

Figure 2. Detail of the movement “B”.

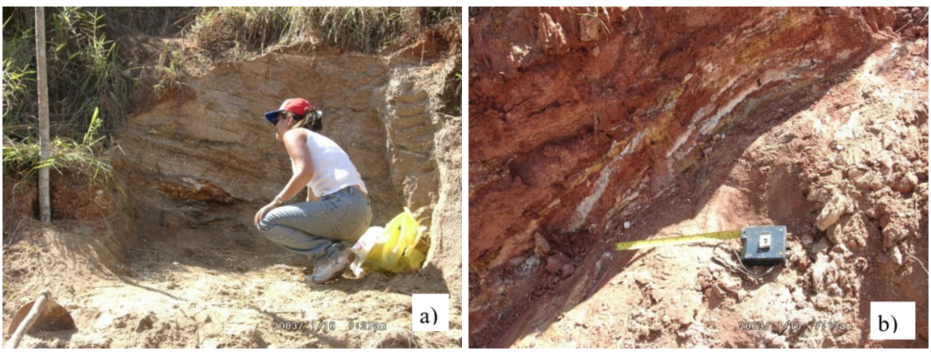

Figure 3. Saprolitic soil: a) typical profile; b) detail of the layers.

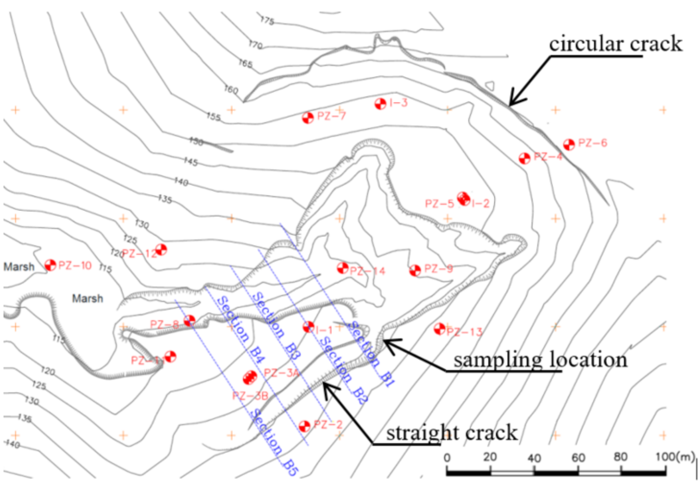

Figure 4. Parallel sections in the topographic chart of the studied area.

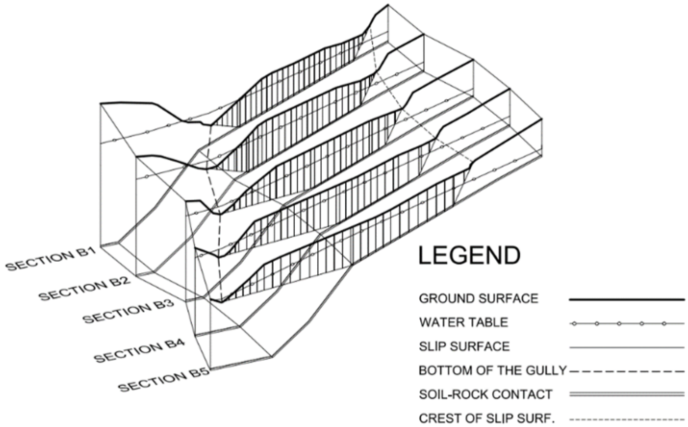

Figure 5. Orthographic projection of the five parallel sections.

3.5. Quasi-three-dimensional method of analysis: Loehr et al.

The Resistance-Weighted procedure was developed by [6] for computing the stability of earth slopes along general slip surfaces, which utilize results from 2D slope stability analyses to estimate three-dimensional stability. Although this quasi-three-dimensional method is approximate, it serves as a simple means for estimating the magnitude of 3D effects when a more rigorous three-dimensional procedure is not available, and it considers more accurately the shape of the failure surface and the influence of the shear strength in each section than the method proposed by Lambe & Whitman [7].

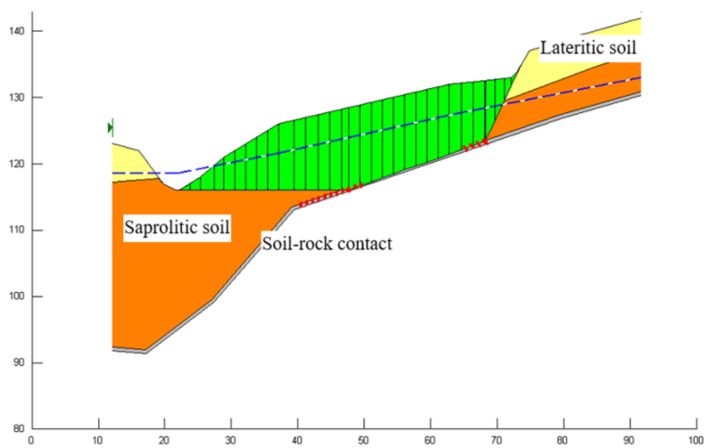

Figure 6. 2D slope stability analysis of section B3 by the Spencer's method, FS_{2D} = 1.322.

The quasi-three-dimensional factor of safety is:

$$FS_{q3D} = \frac{\sum_{i=1}^{n} FS_{2D,i} \cdot T_{t,i}\left({}^{ds}/_{dx}\right)_i}{\sum_{i=1}^{n} T_{t,i}} \tag{2}$$

where the summation is performed for a total of n cross sections taken through the 3D slide mass. $FS_{2D,i}$ is the factor of safety for the ith 2D cross section, $T_{t,i}$ is the equilibrium value of total shear force for the ith cross section and the quantity *ds/dx* is illustrated in Figure 7 in which the simple sliding wedge geometry shows the difference in the projected and actual areas of the sliding surface.

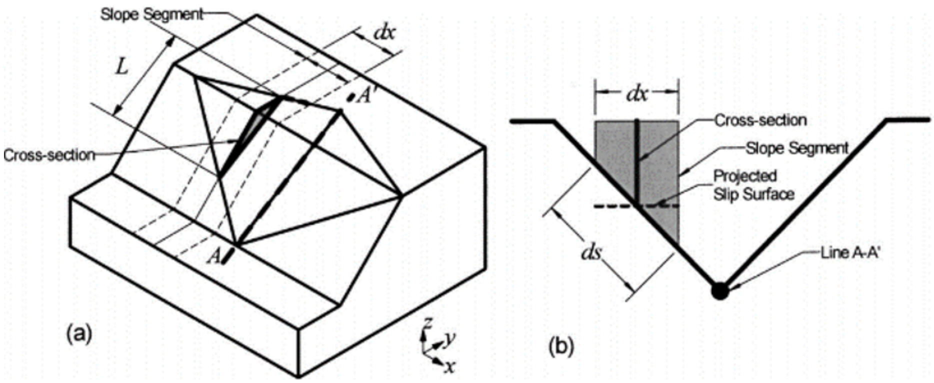

Figure 7. Simple sliding wedge geometry: a) 3D view, and b) cross section perpendicular to A-A'.

4. Results and discussion

Only the sections B2, B3 and B4 were considered in the calculations because the method of Lambe & Whitman [7] was proposed for 3 sections and because the ratio of actual area by projected area, used in the method proposed by Loehr et al. (*ds/dx*) [6], is only available for the three central cross sections. The lengths *ds* and *dx* were measured in Figure 5 and the weight of the soil above the slip surface and the mobilized shear strength were obtained in the slope stability software.

The Table 2 shows the 2D sections considered, their 2D factors of safety, the mobilized value of total shear force, the ratio between the actual area of the slip surface and its horizontal projection and the soil weight.

The average 2D factor of safety of the three sections (FS_{2D}) was 1.260, below the FS_{2D} of the central section. The FS_{q3D} by the method of Lambe & Whitman was 1.277 and the FS_{q3D} by the method of Loehr et al. was 1.313.

It is worth noting that the three decimal places are used only for the sake of comparison, because no slope stability analysis has such accuracy. The factors of safety were above the unity, leading to the conclusion that either the actual shear strength parameters are lower, or the pore-pressures were underestimated (or both). However, that does not influence the comparison among methods. The soil-rock contact may reach a lower friction angle in the residual condition because of its high mica content. That discussion will be carried out in other papers.

Table 2. Data of the cross sections used in the quasi-three-dimensional analyses by [6] and [7].

Sections	$FS_{2D,i}$	$T_{t,i}$ (kN/m)	$(ds/dx)_i$	W_i (kN/m)
B2	1.000	1,514.5	1.060	7,088.3
B3	1.322	1,540.0	1.027	7,463.9
B4	1.457	1,692.8	1.028	8,983.0

A typical procedure in geotechnical practice would be to compute the FS_{2D} of the central cross section while disregarding the 3D effects. If one admits that the quasi-three-dimensional methods provide a better assessment of the slope safety, than the usual procedure would be slightly unsafe in this case, since the FS_{2D} of section B3 is a little higher than the FS_{q3D}. The three factors of safety are similar probably because the sliding block does not have significant restraints on its lateral borders.

5. Conclusions

An active slide and its characteristics were shown. A two-dimensional and two quasi-three-dimensional slope stability methods were used to assess the factor of safety leading to similar results, probably because the shape of the sliding block does not have important restraints on its borders.

Acknowledgements

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