Back-analysis of slope wedge failure in residual soil and comparison with two software results

Fernanda Yamaguchi Matarazo

Pontíficia Universidade Católica de Minas Gerais (PUC MG), Brazil

fernanda.matarazo@ufv.br

Thiago Bretas

Pontíficia Universidade Católica de Minas Gerais (PUC MG), Brazil

thiagobretas@pucminas.br

Abstract

In geotechnical engineering, learning from past mistakes and problems is just as important as pre-construction study. This study was carried out through a back-analysis of a wedge failure in residual soil mass slope, which occurred in 2016 in Bahia state, Brazil. The study developed two numerical models through the Slide® v5 and Swedge® software, both from Rocscience®. Due to the earthmoving works at the site, characterized by re-sloping excavations, a wedge failure occurred in residual soil mass. From the critical section, taken over the failure axis and data from geotechnical investigations available (most SPT sounding), a simplified geological-geotechnical profile was interpreted for numerical modeling purposes. The parameters were initially estimated through empirical correlations with available SPT soundings and later verified by back-analysis. The two surfaces, before and after failure, were obtained through topographic surveys, so the geometry of the failure was studied with adequate precision. Although the residual soil mass (clayey silt) presented homogeneity in its composition, with SPT average values close to 13, the back-analysis revealed extremely low resistance shear parameters with very low cohesion values in both software results, c=3.3kPa through Slide® and c=0.65kPa through Swedge®. For residual soils, specially clayey silts, it was expected higher cohesion values.

1 INTRODUCTION

The analyzed failure occurred in a residual soil mass in 2016 at a construction site of 46 residential buildings in the city of Lauro de Freitas, Bahia state, Brazil. The excavation slope design indicates a total height of 15.0m, separated in 7.25 meters maximum height slopes (1:1) and two intermediate 1.25m wide berms.

To allow the construction of the 46 buildings, the company, for better use of the terrain, invested in earthmoving. According to Fiamoncini (2009) the re-sloping technique is a non-structural, simple and low-cost solution, applicable to any type of soil or rock that consists of excavations in the ground.

For Guidicini and Nieble (1976) when the slope collapses, it is admitted that the safety factor, at the moment of failure, is equal to one.

Therefore, the main objective of this paper is to carry out a critical analysis of the cohesion values considering the observed failure condition, followed by a comparison of the shear strength values found by two different Rocscience software.

Rocscience Slide is a quite common software to analyze 2D slope stability by limit equilibrium. Due to the failure geometry, a wedge, the back-analysis was also carried out using Swedge software, allowing to compare the results (2D x 3D) by different methods.

2 LOCATION OF THE STUDY

The study region is in Lauro de Freitas city, Bahia state, Brazil. The slope is located close to Estrada do Coco (Coconut Road) and Lauro de Freitas city is l26 km far from the Bahia's capital, Salvador city.

According to CPRM (2006, Mineral Resources Research Company), the geodiversity map of the state of Bahia, Lauro de Freitas city is characterized as a recent alluvial plain environment, with variable unconsolidated material, which from the bottom to the top, it's formed by gravel, sand, silt and clayey, concluding it's a residual soil.

Figure 1:View of the studied area dated 03/11/2018 (Google Earth)

The aerial view of the site where the slope back-analysis will be carried out are shown in Figure 1.

In 2012, the earthmoving started at the site of the project, Figure 2.

Figure 2: View of the studied area dated 11/11/2012. (Google Earth)

Figure 3, a satellite image dated 05/08/2016, shows the initial phase of earthworks on the internal streets of the project and the re-sloping processes, at this point, the failure had already occurred with close to 55 m³ sliding mass. The real slope inclinations, after all the earthworks in the site, were close to 47-49° (according to topographic surveys), different from the original design inclination of 45° (1:1).

Figure 3: View of the studied area dated 05/08/2016. (Google Earth)

The Figure 4 shows the front, top and side view of the failure (wedge) and were taken from a drone footage on 03/17/2016.

According with Craig (1978), in general, circular slips are associated with homogeneous, isotropic soil conditions and non-circular slips with non-homogeneous conditions, but the soil where this failure occurred was initially treated as homogeneous soil, but its failure occurred in a non-circular way.

Due to this fact, it was decided to study the failure by back-analysis. Through a visual analysis of the failure, it was noted that the slope failure geometry resembles a wedge. For this reason, it was decided to use back-analysis by Swedge software in addition to the study by Slide software.

Figure 4:Front, top and side view of the failure (Sérgio Velloso Projetos collection)

The soil mass is composed by residual gneiss soil, mostly red or brown clayey silt and sandy silt until 25m deep, from the slope's crest, with medium to very stiff consistency and varying from completely to moderately weathered. From this depth, it occurs gneiss saprolites, slightly weathered, impenetrable to SPT sounding test, with hard consistency. As the analyzed slope has 15m high, maximum, its face is placed on this residual soil.

3 DEFINITION OF INITIAL SOIL PARAMETERS

To determinate the safety factor, using limit equilibrium theory, it is essential to have the soil's parameters (shear resistance), which, for Mohr-Coulomb's envelope, consist in cohesion and friction angle.

Marangon (2009) points out that such parameters can be preferably obtained through specific laboratory tests (direct shear and triaxial test) in the sample of interest. But when test data are not available, it is possible to estimate the shear strength parameters through empirical correlations of in situ tests as the SPT (Standard Penetration Test) sounding, very common in Brazil.

One of the biggest issues of soil studies, especially in Brazil, is the lack of data. According to Marangon (2009), the initial values of shear resistance parameters, for basic design, can be estimated by empirical correlations.

Between the end of 2014 and the beginning of 2015, SPT soundings were carried out near the slope collapse area, before the event.

According to Schnaid (2012), one of the most used expressions to estimate the friction angle is the correlation proposed by Teixeira (1996), Equation 1. Almeida & Oliveira (2018) complements in their study, that this correlation was one of those that came closest to the results obtained through the triaxial test for residual soils in Brazil.

The soil's density was also defined according to the correlations depending on the consistency of fine soils proposed by Godoy (1972) in Cintra *et al.* (2011) , Table 1, since the soil's consistency has been described in the SPT reports.

$$\phi = \sqrt{20 * N_{SPT}{}^{\circ}} + 15 \qquad (1)$$

Table 1: Nspt correlations and specific weight (Godoy 1972 apud Cintra et al., 2011) (adapted)

N (blows)	Consistence	γ (kN/m³)
≤ 2	Very Soft	13
2 – 4	Soft	15
4 – 8	Medium	17
8 - 15	Stiff	19
15 - 30	Very Stiff	20
≥ 30	Hard	21

The Table 2 and Table 3 show the average value of SPT blow number, layer thickness, natural soil's density (γ_{nat}) and friction parameters (Ø) of the soils evaluated in the analyses.

The information of this layer is shaded in Table 2 and Table 3. The water level wasn't identified in both tests.

Table 2: Results of SPT 03

SPT 03 (Borehole top elevation = 38.70 m)				
Textural Description	Layer thickness (m)	N_{SPT}	Ø (°)	γ (kN/m³)
Clayey Silt with sand	1.8	10	29	17

Red Clayey silt with sand	6.0	13	31	19
Red clayey Silt	1.9	10	30	17
Red Clayey Silt with sand	10.3	18	34	19

Table 3: Results of SPT 04

SPT 04 (Borehole top elevation = 35.00 m)				
Textural Description	Layer thickness (m)	Nspt	Ø (°)	γ (kN/m³)
Clayey Silt with sand	0.5	10	29	17
Brown Clayey Silt	1.2	12	30	19
Red Clayey Silt	8.3	19	34	19
Red Clayey Silt with sand	3.0	16	33	19
Brown Clayey Silt with sand	5.0	14	32	19

From the simplified geological-geotechnical soil profile developed, through the data from the SPT sounding tests, it is possible to affirm that the soil under analysis is a gneiss residual soil as mentioned in the map made by CPRM.

4 BACK-ANALYSIS

Mello (1972), Guidicini & Nieble (1976), Wolle (1980), Carvalho et al. (1991) and Augusto Filho & Virgili (1998) mention that back-analysis is one of the most reliable practical way to obtain a quick estimate of average soil shear strength parameters.

According to Guidicini & Nieble (1976), the back-analysis method consists of analyze collapse cases in earth or rock masses. Augusto Filho & Virgili (1998) complement that a back-analysis consist of performing safety factor's calculations adjusting the shear strength parameters, cohesion and friction angle in Mohr-Coulomb envelope, to reach a safety factor (SF) equal to 1.00.

Mello (1972) points out that a slope in an unstable condition, will have a more effective stabilization design if based on the criterion of reestablishing the original SF. Thus, with the simple SF variation, by iterations, it is possible to obtain very satisfactory results, from a technical and economic point of view. However, according to Deschamps & Yankey (2006), back-analysis is reliable only when the model and all the hypotheses are reasonable and represents accurately the real system. For the stability back-analysis of the slope, the software Slide and Swedge were used.

According to Rocscience, Slide is a 2D slope stability program for evaluating the safety factor of circular or non-circular failure surfaces in soil or rocks slopes, by limit-equilibrium theory. In the analysis using the software, three methods were adopted to assess the safety factor: Bishop Simplified (1955), Corrected Janbu (1972) and Morgenstern & Price (1965). Bishop Simplified (1955) was used because it is a more simplified method by verifying just the moment equilibrium. Corrected Janbu (1972) for being a suitable method for homogeneous soil, verifying the horizontal forces equilibrium and Morgenstern & Price (1965) for being a rigorous method, satisfying both forces and moment equilibrium.

The critical section in the Figure 5 describes the profile of the slide before the failure, with simplified horizontal stratigraphy. All the residual soil mass is composed by clayey silt with sand, but it was sub-divided depending on the strength indicated in SPT blow numbers for better characterization of soil behavior.

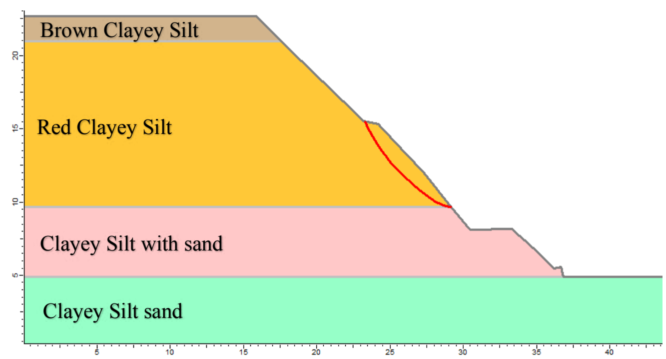

Figure 5: Section used in Slide Analysis

The initial parameters of each layer were defined from correlations with the average Nspt blow numbers found in the SPT tests, mentioned in the item 3. The strength parameters of the brown clayey silt, clayey silt with sand layers were fixed, such as red clayey silt friction angle, varying by iteration only the red clayey silt cohesion (Table 4).

The final shear strength parameters for the red clayey silt, also in Table 4, were measured through several iterations of back-analysis until it results in a safety factor close to 1.0. In this process, the analysis region was limited where the failure really occurred (local analysis), Figure 4, considering a non-circular search algorithm, Figure 6.

The final parameters found by the iterations in Slide software, for the safety factor closest to 1.0, are shown in Table 4. For this condition, the red clayey silt cohesion is 3.3 kPa for a friction angle fixed in 33° (by correlations). The safety factors obtained according to the analysis method used are shown in Table 5.

Table 4: Final parameters

Material	γ (kN/m³)	Cohesion (kN/m²)	Friction Angle (°)
Brown clayey silt	19	10	30
Red clayey silt	19	3.3	33
Brown clayey silt	19	10	32
Hard clayey silt with sand	21	10	34

Table 5: Safety Factors obtained in local analysis

Method	Safety Factor (SF)
Simplified Bishop	1,009
Corrected Jambu	1,003
Morgenstern & Price	1,003

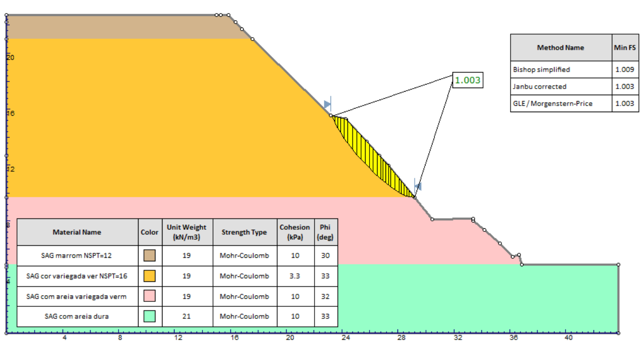

Figure 6: Local analysis with SF=1.0

The global analysis, considering the entire slope surface, Figure 7, was also performed, and the safety factors found were close to 1, indicating consistency of the results of the local and global analysis, they are shown in Table 6.

Table 6: Safety Factors obtained in global analysis

Method	Safety Factor (SF)
Simplified Bishop	0.971
Corrected Jambu	0.973
Morgenstern & Price	0.958

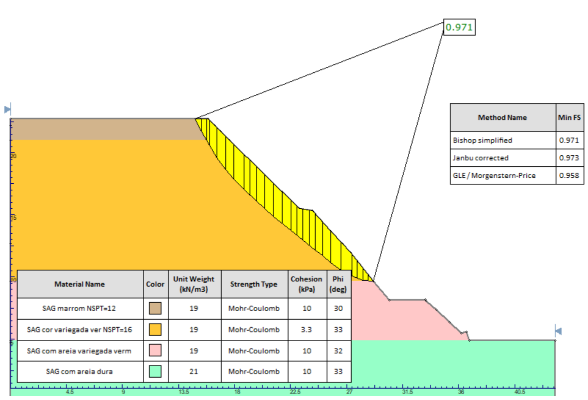

Figure 7: Global analysis with SF=1.0

According to Rocscience, the software Swedge is an interactive analysis tool for evaluating the stability of surface wedges in rock slopes, defined by two intersecting discontinuity planes and the slope surface. The geometry of the failure that occurred in Lauro de Freitas city, Figure 4, is a wedge. So, this exact geometry was modeled in Swedge software, using topographic surveys data, to run the stability analysis.

In Swedge, the input of the slope's geometry is indicated on Table 7. The analysis were performed only for drained condition, Figure 8 and Figure 9, indicating the perspective view and stereographic net obtained.

In the analysis, the friction angle was fixed at 33°, which is the same value used in the analysis made by Slide software, shown in Table 4. Several iterations were performed varying the cohesion until the safety factor results reach value close to 1,00. The safety factor found was 0,99 and the cohesion value for dry condition is 0.65 kPa.

Table 7:Estimated geometry parameters

Wedge	Dip (°)	Dip Direction (°)
Wedge 1	45	135
Wedge 2	45	210

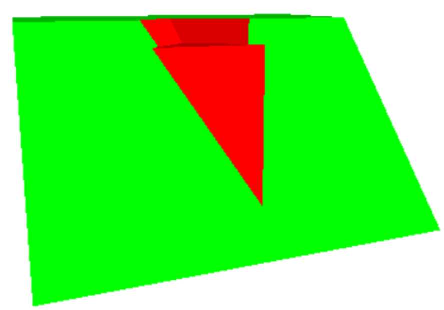

Figure 8: Failure perspective view

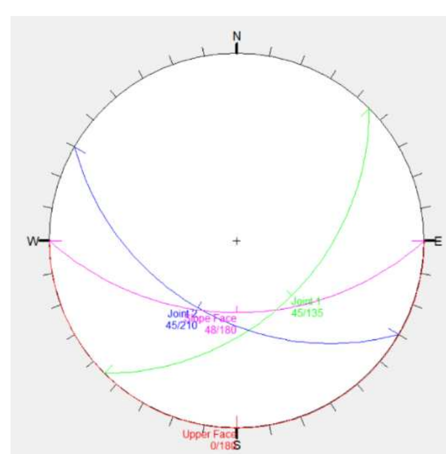

Figure 9: Stereographic net

5 CONCLUSION

This article evaluated the strength parameters of a residual soil in Bahia state, Brazil, through back-analysis by two software, of a wedge failure. The Rocscience's software licenses were available in PUC Minas University for education purposes.

The analysis results of both models, although not identical, indicate that the cohesion value must be very low for the failure occur. For the non-circular failure indicated by Slide, the cohesion found has a value of 3.3 kPa against 0.65 kPa indicated in the wedge failure analysis by Swedge software. Due to 3D effects, the analysis of the failure wedge found lower cohesion value in Swedge, comparing to Slide results. Same conclusion was found by Bretas & Velloso Filho (2018) and Wroth (1984), comparing the strength parameters in back-analysis using Slide2 and Slide3 softwares. The 3D effect increases the FoS, therefore, decreases the strength parameters in back-analysis to find a FoS=1.0.

Although the investigations indicate relatively homogeneous soil, the results presented in the analyses show the importance of a more careful assessment of the local geology.

The reliquary structure on the residual soil led the failure due to anisotropic behavior. The Mohr-Coulomb envelope is not adequate to this residual soil.

6 REFERENCES

Augusto Filho, O. & Virgili, J. C. (1998), Geologia de Engenharia, Cap. 15, Estabilidade de Taludes, ABGE, São Paulo, p. 243-269.

Almeida, M.A & Oliveira, R.M.M. (2018) Estimativa de ângulo de atrito e coesão através de índices de resistência obtidos pela sondagem SPT em solo laterítico e colapsível característico da cidade de Cascavel no Estado do Paraná, COBRAMSEG 2018.

Bretas, T.C. & Velloso Filho, S.M.P. (2018) Retroanálise tridimensional por equilíbrio limite da ruptura de talude em Belo Horizonte/MG, COBRAMSEG 2018.

Carvalho, P. A. S. (Coord.) (1991), Manual de Geotecnia – Taludes de Rodovias: Orientação para Diagnóstico e Soluções de Seus Problemas, Publicação IPT 1843, São Paulo, 410p.

CPRM (Companhia de Pesquisa de Recursos Minerais), (2006). Mapa Geodiversidade do Estado da Bahia. Ministério de Minas e Energia, Brasil.

Cintra, J. C. A.; Aoki, N.; Albiero, J. H (2011). Fundações diretas: projetos geotécnicos. São Paulo: Oficina de Textos.

Craig, R.F. (1978). Craig's Soil Mechanics. University of Dundee, UK.

Deschamps, R., and Yankey, G. (2006). "Limitations in the back-analysis of strength from failures." J. Geotech. Geoenviron.

Fiamoncini, C. M (2009). Estabilização de talude através da técnica de cortina atirantada - estudo de caso. Trabalho de conclusão de curso, Universidade do Extremo Sul Catarinense, UNESC. Criciúma, Santa Catarina.

Guidicini, E. & Nieble, C. M. (1976), Estabilidade de Taludes Naturais e de Escavação, Editora Edgard Blücher Ltda, São Paulo,1976, 170p.

Gomes, C.L.R. (2003), Retroanálise em estabilidade de taludes em solo: metodologia para obtenção dos parâmetros de resistência ao cisalhamento. Campinas, 2003.

Marangon, M. Unidade 04: Estabilidade de taludes. UFJF, 2009. Disponível em: < http://www.ufjf.br/nugeo/files/2009/11/togot_Unid04EstabilidadeTaludes01.pdf> Acesso em: 09/01/2018.

Mello, V. F. B. (1972), Thoughts on Soil Mechanics Applicable to Residual Soils, Southeast Asian Conference on Soil Engineering, 3, Hong-Kong, Proceedings, p.5-34.

Morgenstern, N. R. & Price, V. E. (1965), The Analysis of The Stability of General Slip Surface, Geotechnique, v.15, n.1, p. 79-93.

Schnaid, F. (2012). Ensaios de Campo e Suas Aplicações à Engenharia, São Paulo, Oficina de Textos.

Wolle, C. M. (1980), Taludes Naturais – Mecanismos de Instabilização e Critérios de Segurança, Dissertação de Mestrado, EPUSP, São Paulo, 345p

Wroth, C. P., (1984) The interpretation of in situ tests – Géotechnique 34, No. 4, 449-489p.