Calibration of Strength and Deformability Behaviour of a Residual Soil by the Discrete Element Method

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RESUMO:
O Método dos Elementos Discretos (MED) surge como uma alternativa promissora para modelar taludes em solos residuais. O MED permite uma melhor compreensão dos mecanismos de instabilidade e uma previsão mais precisa da estabilidade do talude. Este estudo realizou a calibração de solos residuais gnáissicos jovens para obter o comportamento de resistência e deformabilidade desses materiais. Para esta calibração, ensaios de compressão biaxial foram modelados no software PFC2D (ITASCA), e os parâmetros calibrados foram o ângulo de atrito, intercepto coesivo e módulo de Young. Os resultados dos ensaios realizados no software foram comparados com os valores obtidos em experimentos reais na literatura. A partir da comparação entre os parâmetros obtidos pelo modelo e aqueles encontrados na literatura, foi possível ajustar as características do modelo até obter resultados satisfatórios para esses parâmetros. Modelos simplificados de taludes em solos residuais foram construídos no PFC2D utilizando os materiais calibrados, e análises de estabilidade de talude pelo Método do Incremento de Gravidade (MIG) foram realizadas nesses modelos para verificar seu comportamento e obter os fatores de segurança dos taludes. Os resultados obtidos das análises no PFC foram comparados com análises anteriores obtidas no Slide (Rocscience).

PALAVRAS-CHAVE: Solo Residual, Método dos Elementos Discretos, Estabilidade de Taludes

ABSTRACT: The use of the Discrete Element Method (DEM) emerges as a promising alternative for modeling slopes in residual soils. DEM allows for a better understanding of instability mechanisms and a more accurate prediction of slope stability. This study carried out the calibration of young gneissic residual soil in order to obtain the resistance and deformability behaviour of these materials. For this calibration, biaxial compression tests were modeled in PFC2D software (ITASCA), and the calibrated parameters were the friction angle, cohesive intercept and Young's modulus. The results of the tests performed in the software were compared to values obtained in real experiments in the literature. From the comparison between the parameters obtained by the model and those found in the literature, it was possible to adjust the characteristics of the model until satisfactory results were obtained for these parameters. Simplified models of slopes in residual soils were built in PFC2D using the calibrated materials, and slope stability analyses by the Gravity Increase Method (GIM) were performed on these models to verify their behaviour and obtain the safety factors for the slopes. The results obtained from the PFC analyses were compared to previous analyses obtained from Slide (Rocscience).

KEYWORDS: Residual Soil, Discrete Element Method, Slope Stability

1 INTRODUCTION

Slope stability is one of the most unpredictable problems in geotechnical projects and the cause of this can be returned to ambiguity in several factors such as condition and location of failure, geotechnical parameters of soil and history of loading on the slope (Asoudeh & Oh, 2014). Slope failures in residual soil and weathered rock are common in humid temperate and tropical climates. The profile of weathering which has developed on a rock slope over a long period of geologic time has altered the strength characteristics of the slope so as to increase its susceptibility to failure (Deere & Patton, 1971).

Finite element methods are commonly used in geomechanics to model the response of soil. A disadvantage of these methods is that there may not exist a suitable stress-strain law for the material. Secondly, the natural development of cracks and failure surfaces is not well represented (Cundall, 2001).

In DEM models, loads and deformations can be applied to virtual samples to simulate laboratory tests, and particle-scale mechanisms can be analysed. Failures in geomechanics often involve large displacements or deformations, and DEM models can contribute to our understanding of important failure mechanisms, being highly suitable for the simulation of the landslide process (O'Sullivan, 2011; Zhao *et al.*, 2021).

This paper presents the calibration process for 2 samples of saprolitic soils from gneiss, in different weathering conditions, and the slope stability analyses of generic slopes composed of these soils using the DEM. These results are compared to results obtained by the limit equilibrium method (LEM) in Slide.

2 LITERATURE REVIEW

2.1 Residual Soils

Generally, soils that have weathered in situ are considered residual. The factors of climate, temperature, parent material, water movement, age and vegetation are responsible for the resulting soil profile. Optimization of these factors occurs in tropical regions where heavy rainfall and warm temperatures are most conducive to chemical weathering and deep residual soil profiles develop (Townsend, 1984).

A typical weathering profile consists of different horizons ranging from fresh rock, weathered rock to residual soil. If the soil exhibits characteristics of the parent rock, relic structures, it is classified as "young residual soil" or "saprolitic soil". If no detectable relic structure is present, the term "mature residual soil" is used (Cirone, Vargas Jr. and Campos, 2020). Figure 1 presents typical profiles from different parent rocks.

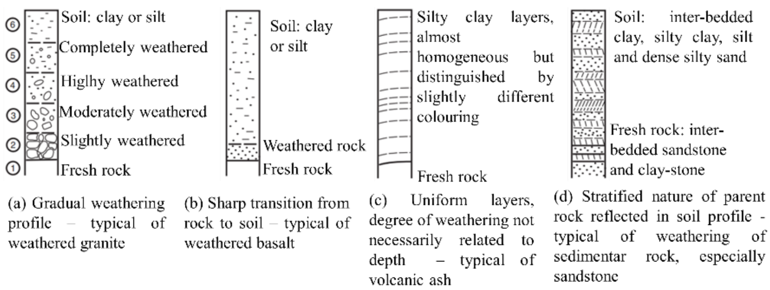

Figure 1. Variations in residual soil weathering profiles (modified of Wesley, 2010).

2.2 Residual Soil Slope Stability

The understanding of slope stability in residual soils depends on recognizing the role played by weathering profiles, groundwater levels, and relic structures in these slopes (Deere and Patton, 1971). The combination of deeply weathered soils, steep slopes, and intense rainfall makes tropical regions more prone to mass movements (Santos Jr., Lacerda, and Ehrlich, 2020).

Some failure modes are especially related to residual soils, weathered rocks, and associated colluvium (Deere and Patton, 1971). Slope failures in residual soils are unlikely to be deep-seated circular failures. They are more likely to be relatively shallow, with fairly planar failure surfaces. In large slopes with a limited layer of overlying weathered material on top of solid rock, they are likely to be predominantly translational slides (Wesley, 2011). Some failure modes that are particularly common in weathering profile materials and colluvium are shown in Figure 2.

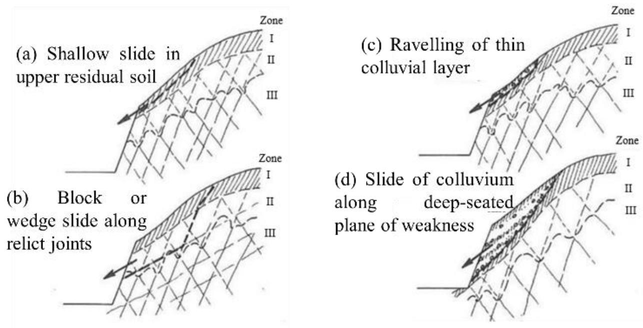

Figure 2. Common types of slides in weathered rock, residual soil and colluvium (modified of Deere & Patton, 1971)

2.3 Discrete Element Method

Numerical modeling in soil and rock using discrete particle methods captures the complicated behavior of real materials with simple assumptions and few parameters at the microscopic level. The overall complex behavior arises as an emergent property of the assembly (Cundall, 2001). In this context, DEM was introduced by Cundall (1971) for the analysis of rock mechanics problems and later applied to soils by Cundall and Strack (1979).

In DEM, the interaction of particles is a dynamic process with equilibrium states developing whenever internal forces balance. Movements result from disturbances propagated by the movement of walls and particles, external forces, and body forces through the particle system.

The dynamic behaviour is represented by a time-stepping algorithm. DEM is based on the idea that the time step is so small that during a single time step, disturbances cannot propagate from any particle beyond its immediate neighbours. Thus, at all times, the forces acting on any particle are determined exclusively by its interaction with the particles with which it is in contact. Physical instability can be easily modeled without numerical difficulty because failure processes occur realistically, without the need to invoke a non-physical algorithm, as is done in some implicit methods (Cundall, 1979; Potyondy and Cundall, 2004).

3 MATERIAL CALIBRATION PROCESS

The present study was based on investigations carried out by Futai, Almeida and Lacerda (2004) on a tropical soil profile. The soil profile comprises a reddish lateritic layer underlain by a saprolitic soil from which a number of block samples were taken. This particular study concentrates on 3 samples of the saprolitic soil horizon, which are the 3, 5 and 7 m deep saprolitic soil samples.

Strength tests performed in samples from 5 m depth were used in order to calibrate the material for the PFC model. The values for natural unit weigth, cohesion and friction angle are presented in Table 1.

Table 1. Values for soil properties and parameters of the samples (Futai, Almeida and Lacerda, 2004).

Depth (m)	c' (kPa)	φ (º)	γ_{nat} (kN/m³)
3	8	29.6	19
5	15	31.0	17.5
7	20	25.4	17.5

The Young's modulus were obtained from the initial stage of the stress-strain curve from undrained triaxial tests on 5 m deep sample, presented in Figure 3. It was evaluated as a secant stiffness for the interval between deviatoric stress $q = 0$ and $q = \frac{q_{máx}}{2}$.

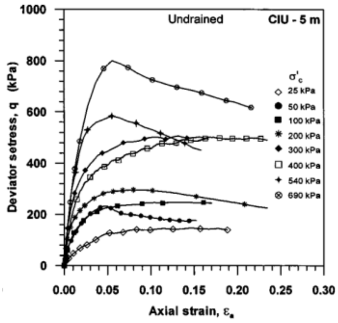

Figure 3. Results of undrained tests on samples from 5 meters depth (Futai, Almeida and Lacerda, 2004).

The determination of Young's modulus is given by the Equation 1.

$$E_{50} = \frac{\Delta q}{\Delta \varepsilon_a} \tag{1}$$

The values obtained for the axial strains, major stresses and calculated Young' modulus are presented in
Table 2.

Table 2. Values of axial strain, major stress and calculated Young' modulus.

σ_c' (kPa)	Δq (kPa)	ε_a(%)	E_{50} (kPa)
100	129	1.15	11217
200	150	1	15000
400	252	1.4	18000

For the calibration process of the material in PFC, a virtual test specimen that represents the soil to be calibrated was created. In this study the particle packing mesh for the virtual specimen was created on GiD Simulation software. To create the specimen, the RBall mesher was used, by the Optimization radius method, which is a iterative method that optimizes distances and positions of particles for minimum porosity. The virtual specimen model contais 839 particles and their average radius is 0.5 meters, and the biaxial testing box has dimensions of 10 meters horizontally and 20 meters vertically. Once the mesh was created in GiD, it was imported into PFC, creating particles in the same positions and sizes.

The PFC software has a series of built-in contact models to represent different contact interactions between particles. The particle contact model chose to represent the material was the Linear Parallel Bond Model (PBM). The linear microproperties calibrated were the normal stiffnes (Kn), effective modulus (Emod), normal-to-shear stiffness ratio (Kratio), friction coefficient (Fric). The parallel bond group microproperties calibrated were the normal stiffness (Pb_kn), shear stiffness (Pb_ks), tensile strength (Pb_ten), cohesion (Pb_coh) and the friction angle (Pb_fa), shown in Table 3.

Table 3. Calibrated microproperties for the Linear Parallel Bond Model.

Depth(m)	Kn	Emod	Kratio	Fric	Pb_kn	Pb_ks	Pb_ten	Pb_coh	Pb_fa
3	5e07	7e06	1.5	0.7	3e07	3e06	8e03	6e03	35
5	5e07	7e06	1.5	0.7	3e07	3e06	8e03	6.002e03	45
7	6e07	8e06	1.5	0.3	3e07	3e06	9e03	9e03	35

In order to obtain the calibrated micro-properties, biaxial compression tests were performed in the PFC virtual specimen for 100, 200 and 400 kPa confining pressures. A servo-control mechanism was used on the side walls, which controls the velocity and displacement of these walls to maintain constant confining pressure. The Rball GiD mesh and the virtual test specimen in PFC are shown in Figure 4.

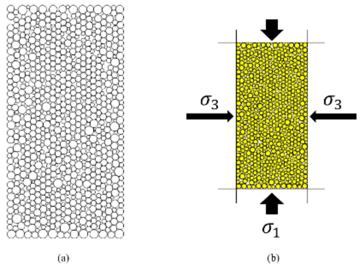

Figure 4. (a) Rball GiD particles mesh; (b) Scheme of biaxial compression test on PFC2D virtual specimen

The calibration process consists of obtaining parameters representative of the material macro mechanical behaviour through the microproperties existing in PFC. Therefore, the microproperties are adjusted by trial and error until representative macro property parameters are obtained. For this purpose, stress-strain curves are obtained, from which Young's modulus values are extracted. With the curves, it is possible to construct a material strength envelope in order to obtain the strength parameters. The stress-strain curves and the strength envelopes obtained are shown in Figure 5, Figure 6 and Figure 7.

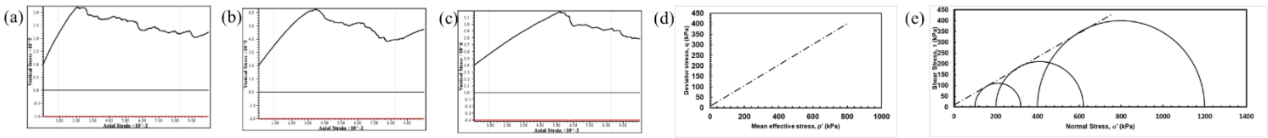

Figure 5. 3 meter depth sample. Stress-strain curves for the following confining pressures: (a)100 kPa; (b) 200 kPa; (c) 400 kPa; (d) q-p' strength envelope; (e) Mohr-Coulomb strength envelope.

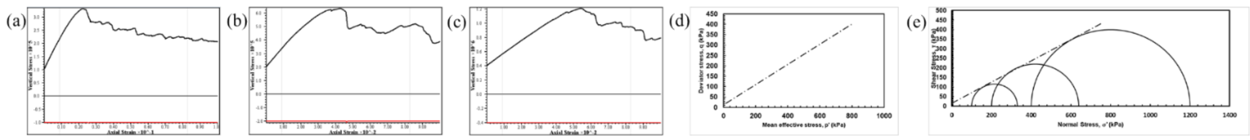

Figure 6. 5 meter depth sample. Stress-strain curves for the following confining pressures: (a)100 kPa; (b) 200 kPa; (c) 400 kPa; (d) q-p' strength envelope; (e) Mohr-Coulomb strength envelope.

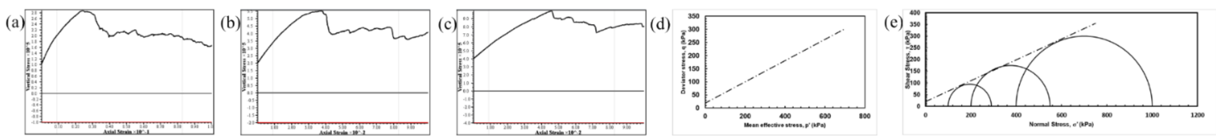

Figure 7. 7 meter depth sample. Stress-strain curves for the following confining pressures: (a)100 kPa; (b) 200 kPa; (c) 400 kPa; (d) q-p' strength envelope; (e) Mohr-Coulomb strength envelope.

The Young's modulus obtained are presented in Table 4.

Table 4. Young's modulus obtained by calibration process.

Depth (m)	σ_c' (kPa)	Δq (kPa)	ε_a(%)	E_{50} (kPa)
	100	110	0.87	12644
3	200	210	1.3	16154
	400	400	2.22	18018
	100	115	0.86	13372
5	200	220	1.145	15172
	400	400	2.22	18018
	100	95	0.8	11875
7	200	175	1.2	14583
	400	300	1.8	16666

The Young's modulus values obtained in the calibration showed a slight difference compared to the experimental values, however, the difference is acceptable. Additionally, the values obtained in the experimental tests on samples at 5 meters depth were adopted for the calibration of materials at 3 and 7 meters depth as well. It would be expected that there would be changes in the deformability parameters for these samples, but they were considered negligible for the purposes of the present study.

4 SLOPE STABILITY ANALYSIS

4.1 Limit Equilibrium Method Analysis

Slope stability analyses were conducted in the Slide software (Rocscience) using the general method of limit equilibrium (GLE/Morgenstern-Price). The obtained safety factors were then compared to the results obtained by the DEM. The strength parameters used in Slide are presented in Table 5.

Table 5. Strength parameters obtained from calibration process.

Depth (m)	c' (kPa)	φ (º)
3	9	29
5	15	29
7	21	24

The values obtained in the calibration show a slight variation when compared to the values obtained by the experimental tests performed (Futai, Almeida and Lacerda, 2004).

The analysis were performed for a generical slope geometry, with a slope angle of 30º and slope height of 40 meters. The results for the slope stability analysis and the safety factors obtained by LEM are presented in Figure 8.

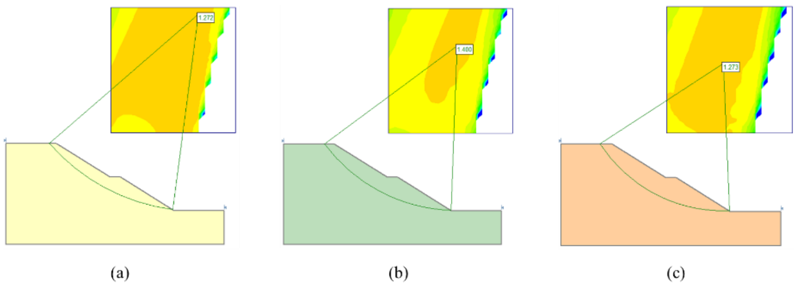

Figure 8. Slope stability analyses results in Slide for saprolitic soil samples. (a) 3 m depth; (b) 5 m depth; (c) 7 m depth.

It was obtained 1.272 and 1.273 as the safety factor values for the samples at 3 and 7 meters depth, respectively, these values can be considered equal for engineering purposes. However, the sample at 5 meters depth presented a safety factor of 1.4, slightly higher than the other two. The critical failure surfaces for all three cases are starting from the crest of the slope and passing through its toe.

4.2 Discrete Element Method Analysis

For the slope stability analysis in PFC, a generic model with the same geometry as the one used in Slide was constructed. Firstly, the particle mesh was generated in GiD using the same parameters as those used for generating the specimen for the biaxial tests. This is because in DEM, the distribution and size of particles influence the model response. The slope model contais 23125 particles and their average radius is 0.5 meters. The slope model generated in GiD was imported into PFC. Additionally, the calibrated microproperties for the BPM contact model were added to the particles in the slope model.

The strength reduction method (SRM) was applied to obtain the safety factors in DEM. This method involves reducing the material properties until failure occurs. For the current study, the reduced properties were the friction coeficiente (Fric), tensile strength (Pb_ten), cohesion (Pb_coh), and friction angle (Pb_fa). Starting from the original values of these properties, they were divided proportionally and simultaneously by

1.1, 1.2, and so on until the model exhibited instabilities. The safety factor is calculated based on dividing the original values of the properties by their values at the moment of instability.

The results obtained are presented in Figure 9, Figure 10 and Figure 11.

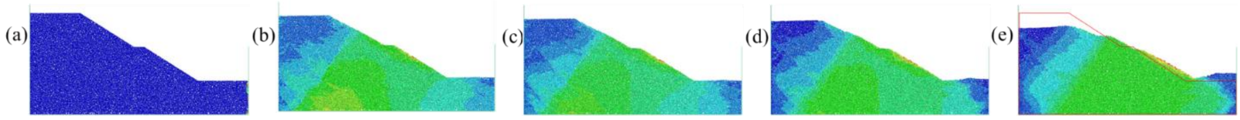

Figure 9. Horizontal displacement of particles at: (a) 0 cycles (b) 7000 cycles (c) 10000 cycles (d) 20000 cycles (e) 50000 cycles (3 meters deep sample).

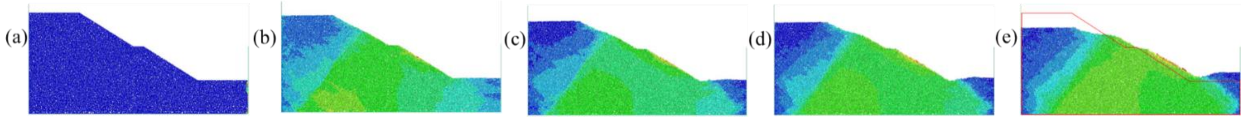

Figure 10. Horizontal displacement of particles at: (a) 0 cycles (b) 7000 cycles (c) 16000 cycles (d) 25000 cycles (e) 50000 cycles (5 meter deep sample).

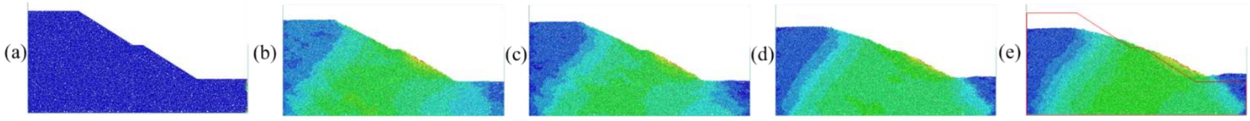

Figure 11. Horizontal displacement of particles at: (a) 0 cycles (b) 7000 cycles (c) 13000 cycles (d) 25000 cycles (e) 35000 cycles (7 meters deep sample).

The color scale represents the displacement of particles in the horizontal direction. It can be observed that initially circular surfaces form near the face of the slope with greater horizontal displacements than the rest of the slope. However, throughout the analysis, the failure does not occur localized along these surfaces. In the figures with more cycles the slope moves almost homogeneously horizontally. The last figures on the right show the original geometry of the slope in a red perimeter. It is observed that the vertical displacement of the slope crest is quite significant, reaching about 9 meters after 50000 cycles. The consolidation of particles as a whole is also significant. Finally, a uprising at the toe of the slope can be observed.

For the slopes with parameters from the samples of 3 and 5 meters depth, safety factors of 1.2 were obtained, while for the sample of 7 meters depth, a safety factor of 1.3 was obtained. Analyzing the obtained safety factors it can be observed that the higher cohesive factor in the slope with parameters from the 7 meter depth sample may have influenced this slightly higher safety factor. It is noted that the safety factors of the slopes from the samples of 3 and 7 meters depth coincide, for engineering purposes, with the factors obtained with the LEM. However, the safety factor obtained for the slope of the 5 meters depth sample was lower in the DEM. Considering that the calibrated cohesion microproperty (pb_coh) was practically identical between the samples of 5 and 3 meters depth, it reinforces the idea that the cohesive property significantly influenced the behavior and resistance of the materials in the DEM analysis.

5 CONCLUSION

The present study conducted the calibration of saprolitic soils in PFC2D and utilized this calibrated model to construct a slope model and perform stability analyses using the method of strength reduction.

It was observed that, in general, calibration through virtual biaxial compression tests was able to obtain strength and deformability parameters very close to those obtained experimentally.

It was noted that micro parameters related to friction and cohesion have a certain influence on the material's cohesion parameter, as well as the micro parameter related to cohesion influences the friction angle. Therefore calibration must be done by trial and error, considering that changes in micro parameters not only affect the macro parameter to which they are related.

In terms of safety factors, the DEM obtained values close to those found by the LEM. However, it was observed that possibly for analyses performed by the DEM, the micro cohesion properties have a greater influence on the stability of the slope model than properties related to friction.

The analyses performed by the DEM allowed observing a series of phenomena related to large displacements, deformations, and post-failure in the model, reinforcing the idea that the DEM emerges as a powerful tool for landslide analyses and other geotechnical engineering related issues.

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