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MECHANICAL INVESTIGATION OF AN ANOMALOUS CLAYEY SAND SOIL USED AS LANDFILL COVER LAYER

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Abstract. Given the increase in the purchasing power of population, there is an increment in waste generation. Considering it and the scarcity of adequate areas for final disposal of municipal solid waste, it is recurrent that landfills' managers invest in increasing the load capacity of landfills. Then, landfills are work of high geotechnical risk in terms of slope stability. Thus, it is important to investigate the mechanical behavior and stability of landfill's slopes. It should also be noted that the deposits of soil, when mined for raw material supply to compose landfill cover layers, become less stable representing risks to local workers. Therefore, it is important to verify the stability of soil deposits too. In this sense, this paper proposes a geomechanical investigation on the landfill slope stability, as well as on the soil deposits' slope. Experimental and numerical analyzes were performed. Experimental ones consist of soil's grain size characterization, soil compaction, and direct shear tests in natural condition, from which the needed parameters to proceed with numerical analyzes were obtained. Numerical analyzes integrate two modeling developed by a software applying the limit equilibrium method improved by Morgenstern & Price. The soil was classified as a clayey sand; it presented an expected friction angle (34.8º) for a sandy soil, but cohesion (56.6 kPa) was above the expected for a soil with 69% of sand. From numerical modeling, it was observed that the soil deposit is stable with FS = 3.1, as well as the landfill cell, which presented FS = 2.2.

Keywords: Environmental geotechnics, Slope stability, Shear strength, Numerical modeling

1 Introduction

Given the increase in industrial activities and the purchasing power of population, there is also an increment in waste generation rates. According to the World Bank Group report entitled What a Waste 2.0, prepared by Kaza et al. [1], 2.01 billion tons of waste per year are currently generated worldwide, but the perspective is that this value will grow dramatically, reaching 3.4 billion tons by 2050. Considering this scenario and the scarcity of adequate areas for final disposal of municipal solid waste (MSW) (SANTOS et al.) [2], according to Remédio [3], it is recurrent that landfills' managers invest in increasing the load capacity of landfills in operation, or in the reuse of former closed MSW disposal areas.

In this context, in addition to presenting problems of sanitary nature, landfills are a high-risk geotechnical work in terms of slope stability since they offer dangers to workers, waste pickers, irregular constructions in the surroundings, and local population. Instability in landfills may occur for numerous reasons: improper waste compaction, inadequate internal and external drainage systems, biological decomposition of organic waste with potential for sliding, increase in humidity with consequent increment in pore water pressure, increase in internal pressure caused by gases pockets trapped in the waste mass, inefficient cover layer, and last but not least, solicitant stress overcoming the resistant ones (ERING & BABU) [4].

There are numerous documented cases in the literature that portray accidents occurring in landfills, which are often due to instability of slopes. One of the major landfill accidents, which caused the death of more than 330 people, occurred at the Payatas Landfill, on the outskirts of Manila, Philippines. According to Chen et al. [5], after ten days of heavy rains, a slope failure causing the geotechnical accident. Other authors who report numerous accidents are Jahanfar et al. [6]; according to them, one of the first major landfill accidents occurred in 1977, in Sarajevo, Yugoslavia, causing the movement of more than 200,000 m^3 of MSW. Jahanfar et al. [6] still report the accident that occurred in 1997 due to slopes' failures in Bogota landfill (Colombia); in 2005, in Bandung landfill (Indonesia), another accident killed hundreds of people. Benvenuto et al. [7] report two accidents that occurred in the state of São Paulo, Brazil: the first one, in 1991, in the Bandeirantes Landfill, moved more than 65,000 tons of waste mass, and the second one, which moved more than 220,000 tons of waste in the Sítio São João Landfill, in 2007. Benvenuto et al. [7] point out that despite the difficulties peculiar to the publication of accident data, when such cases can be studied, there is a great contribution to development and improvement of construction and operational techniques related to the safety of sanitary landfills. It is worth mentioning that accidents involving landfills, in addition to causing loss of life, also cause environmental degradation and demand high costs with the necessary repairs.

Thus, it is undoubtedly important to investigate the mechanical behavior and stability of landfill's slopes. It should also be noted that the deposits of soil, when mined for raw material supply to compose landfill cover layers, become increasingly steep and less stable representing risks to local workers. Therefore, it is important to verify the stability of soil deposits in order to promote safety of those who work in mining activities. In this sense, this paper proposes a geomechanical investigation on the landfill slope stability, as well as on the soil deposits' slope where soil has been exploited to construct the landfill cover layer.

Belfort et al. [8], when investigating a soil applied as cover layer, classified it as clayey sand. The authors also performed a field test to determine the permeability of the soil, and they found that it presented anomalous behavior in terms of water flow. The soil permeability was of the order of 10^{-10} m/s, which is about 10,000 times lower than the permeability of some clays with typical flow behavior (10^{-6} m/s). Hence, in this work the mechanical resistance of a soil sample collected at the cover layer of the landfill in the municipality of Altinho - BR is evaluated; the paper's objective is to obtain the necessary parameters for the numerical analysis of the slope stability of the landfill and the soil deposit which has been mined. It should be noted that the soil studied in this paper comes from the same region where Belfort et al. [8] collected the soil sample studied by them.

2 Methodology

For elaborating this paper, experimental analyzes were initially performed, followed by numerical ones. Experimental analyzes consist of soil's grain size characterization, soil compaction, and direct shear tests in natural condition, from which the needed parameters to proceed with the numerical analyzes were obtained. The numerical analyzes integrate two modeling developed by the software GeoSlope to study the geomechanical behavior of the established scenarios.

2.1 Experimental methodology

Grain size characterization tests were performed according to the procedures described in NBR 7181 [9]. Grain size characterization, which is performed by sedimentation of finer materials and sieving of coarse materials, were performed with the scope of determining the soil grains size and their respective percentages of occurrence.

Soil compaction was carried out according to NBR 7182 [10] with the objective of identifying the optimum moisture content, as well as the maximum dry unit weight of the sample tested.

In order to determine soil strength parameters, direct shear test was chosen. This test is based on the Mohr-Coulomb failure criterion to determine the shear strength of soils. In the direct shear test the soil is placed in a box, which is divided by a straight plane in two halves of equal thickness. At the top of this experimental configuration the sample is subjected to a vertical force N, and the box's upper half is subjected to a tangential force T as shown in Fig. 1.

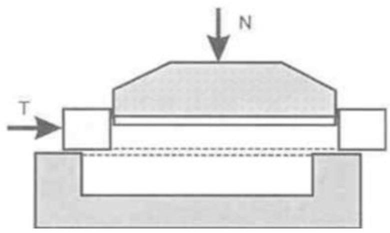

Figure 1. Diagram of the equipment used in the direct shear test. Note: Pinto [11]

The upper part of the box is displaced horizontally by the action of the T force, which generates shear stresses in the sample until its rupture in the imposed horizontal plane. To obtain the acting stresses, the forces (T and N) are divided by the cross-sectional area.

In this paper, the procedures determined in ASTM D3080 [12] were followed; it is a standard that describes the methodology of direct shear test under natural conditions.

When proceeding with the test, the objective was to obtain through the interpretation of a linear rupture envelope the cohesive intercept and the internal friction angle of the soil. It is noteworthy that the specimen was cubic in shape with 5.08 cm of side, according to the scheme presented in Fig. 2; it was molded from a compacted sample with water content corresponding to the optimal moisture. The axial loads applied during the test were 100, 200 and 300 kPa. It is informed that all experimental tests were performed at the Soil and Instrumentation Laboratory of the Federal University of Pernambuco (UFPE).

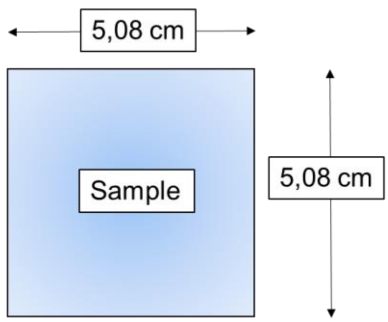

Figure 2. Cubic specimen scheme

2.2 Numerical Methodology

In order to investigate the stability of the proposed scenarios, two numerical models were carried out using the software GeoSlope, which made it possible to evaluate the material geomechanical behavior.

By using this software, it was feasible to investigate the slope stability applying the limit equilibrium method. This technique has several methodologies, such as Modified Bishop, Spencer, Fellenius (SOARES & ARAÚJO) [13], among others. The limit equilibrium method was initially developed by Fellenius [14], and it continues to be vastly improved over the years.

One of the authors who improved the method was Morgenstern & Price [15]; it is noteworthy that in this study, this method was chosen. From these authors, several others have used the limit equilibrium method to investigate the slope stability in many geotechnical engineering works (SUN et al.; JIN et al.; ZHU et al.) [16, 17, 18].

The limit equilibrium method not only calculates the balance of forces in the horizontal and vertical directions, but also verifies the balance of moments (ATASHBAND) [19]. Because of this, this methodology is one of the most rigorous when compared to other limit equilibrium models, such as Fellenius, Bishop, among others (AGUILERA) [20].

In order to this method verify the impediment of slice rotation, as outlined in Fig. 3, its formulation begins with the moment balance originating at the midpoint of the slice base, whose general equation is described in Eq. (1) (MORGENSTERN & PRICE) [15].

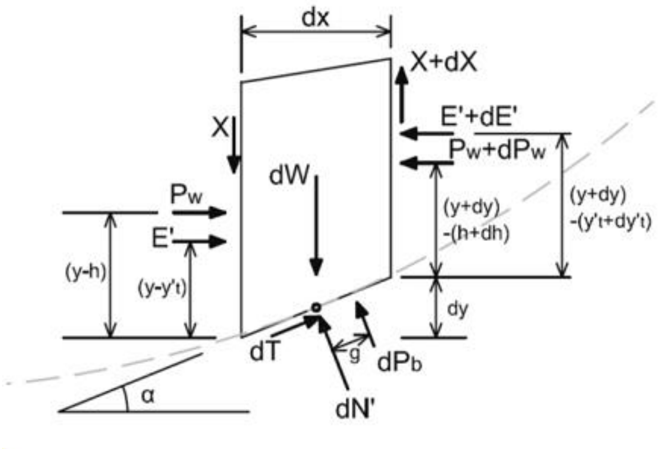

Figure 3. Generic slice and force polygon for the Morgenstern-Price method. Note: Silva [21]

$$
\begin{aligned}
&E'\left[(y-y'_t)-\left(\frac{dy}{2}\right)\right]+P_w\left[(y-h)-\left(-\frac{dy}{2}\right)\right] \\
&-(E'+dE')\left[y+dy-y'_t-dy'_t+\left(-\frac{dy}{2}\right)\right]-X\frac{dx}{2} \\
&-(X+dX)\frac{dx}{2}-(P_w+dP_w)\left[(y+dy)-(h+dh)-\frac{dy}{2}\right] \\
&-dP_b.g=0.
\end{aligned} \tag{1}
$$

In which:
E' - Effective normal force of interaction;
X - Tangential force of interaction;
dW - Slice weight;
P_w - Resulting from neutral pressures acting on the lateral face of the slice;

dP_b - Resulting from neutral pressure at the base of the slice;
dN' - Effective normal force at the base of the slice;
dT - Cutting force at the base of the slice;
α - Slice base inclination.

Then, the balance of forces is performed in the direction of N, Eq. (2), and in the direction of T, Eq. (3).

$$dN' + dP_b = dW cos\alpha - dX cos\alpha - dE' sin\alpha - dP_w sin\alpha. \quad (2)$$

$$dT = dE' cos\alpha + dP_w cos\alpha - dX sin\alpha - dW sin\alpha. \quad (3)$$

Even so, although this numerical model is considered one of the most complete, it is necessary to highlight that the limit equilibrium method has limitations such as performing a static analysis with assumption of uniformly distributed stresses (MORGENSTERN & PRICE) [16].

2.3 Numerical Modeling

The first scenario investigated in this paper is characterized by the mining of a soil deposit with the objective of simulating the exploration of the studied soil in the field.

The contour geometry of the ground, which is shown in Fig. 4, is represented by a slope of inclination 1H:1V, with 10 m height and 10 m length. This inclination was the same identified in the field; however, height was generated twice higher.

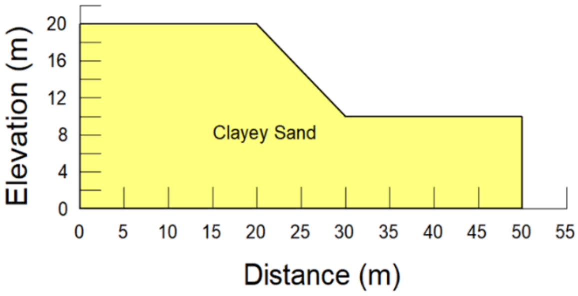

Figure 4. Contour geometry of the soil deposit

In this simulation, the parameters used for the analysis were obtained in the laboratory as described in subsection 2.1.

The second numerical analysis aimed to evaluate the viability, in geomechanical terms, of using the geometry illustrated in Fig. 5 for the landfill cell, applying the soil from the deposit as a cover layer.

For this purpose, a hypothetical landfill cell was simulated with 50 m long, 10 m height and a cover layer with thickness of 1 m.

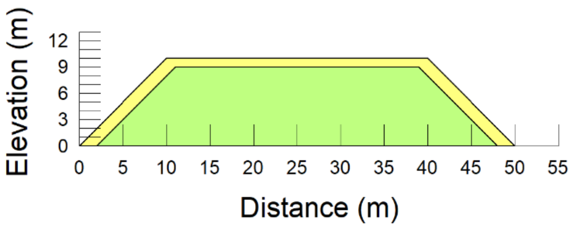

Figure 5. Hypothetical landfill cell

In this simulation, it was applied the soil parameters, which was collected at the landfill cover layer, obtained according to the methodology described in subsection 2.1. Regarding the parameters of MSW stored inside the cell, literature parameters obtained for a new age MSW were used. The parameters identified were friction angle and internal cohesion of the waste according to Landva & Clark. [22], as well as the dry unit weight according to Gay et al. [23]. Table 1 shows the parameters of MSW applied in this study.

Table 1. Parameters of the new age MSW. Note: Landva & Clark [22] e Gay et al. [23]

Material	Cohesion (kPa)	Friction angle (°)	Dry unit weight (kN/m^3)
MSW	23	24	10

3 Results

3.1 Experimental results

From the grain size characterization tests and according to the Unified Soil Classification System (SUCS), it was identified that the soil studied is classified as clayey sand (SC), with 69% of sand. Table 2 shows the soil granulometric composition:

Table 2. Granulometric composition of the soil in percentage (%)

Gravel	Coarse sand	Medium sand	Fine sand	Silt	Clay
5	11	26	32	10	16

According to compaction test, maximum unit weight of the sample is 19.16 kN/m^3 and the maximum water content is 12%. Fig. 6 shows the compaction curve of the soil sample.

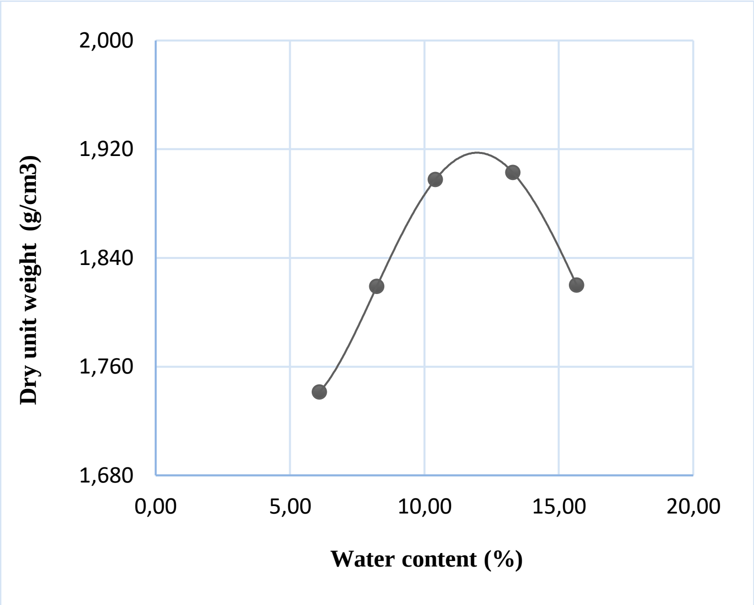

Figure 6. Compaction curve of the soil

The direct shear curve of the sampled soil is presented in Fig. 7. According to this test, it was determined that the soil cohesion is 56.6 kPa and the internal friction angle is 34.8º. It is worth mentioning that the coefficient of determination (R^2) of the linear failure envelope was equal to 0.9894, a value very close to 1.00. This fact indicates that the experimental test was developed with high quality standard; therefore, it produced a curve model that fits the sample satisfactorily.

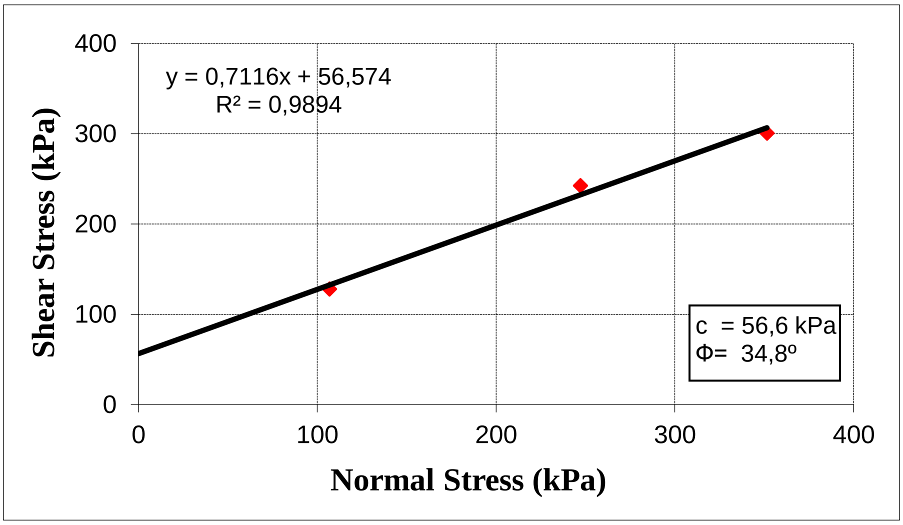

Figure 7. Direct shear curve of the sampled soil

Thus, Table 3 presents the soil parameters obtained through the experimental tests, which were subsequently applied in the numerical analyses.

Table 3. Soil parameters obtained through the experimental tests

Material	Cohesion (kPa)	Friction angle (°)	Dry unit weight (kN/m^3)
Clayed Sand	56.6	34.8	19.16

3.2 Numerical results

Considering that a slope becomes unstable for factor of safety less than or equal to 1, it is observed in Fig. 8(a) that the most unstable surface for the soil deposit scenario presents a factor of safety (FS) considered stable, FS = 3.1, which indicates that there is no risk of collapse for the analyzed scenario.

Fig. 8(b) shows a color map that highlights the zone with the lowest and highest factor of safety, so that the red zone has the lowest factor of safety.

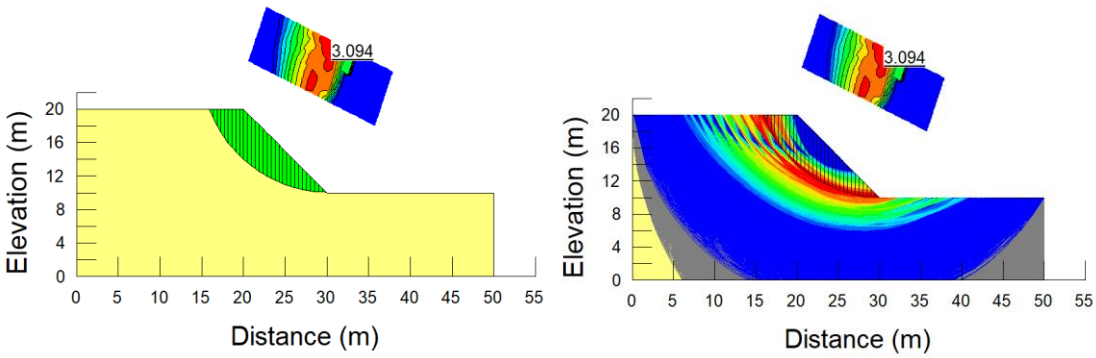

Figure 8. (a) critical surface and (b) factor of safety map for the soil deposit in scenario

Fig. 9(a) shows that for the proposed landfill scenario, the single cell configuration was stable with a factor of safety greater than 1.5, FS = 2.2. In addition, it is observed in Fig. 9(b) the factor of safety map, in which it is identified that the critical FS zone starts at the top of the slope from the first 10 m of the crest.

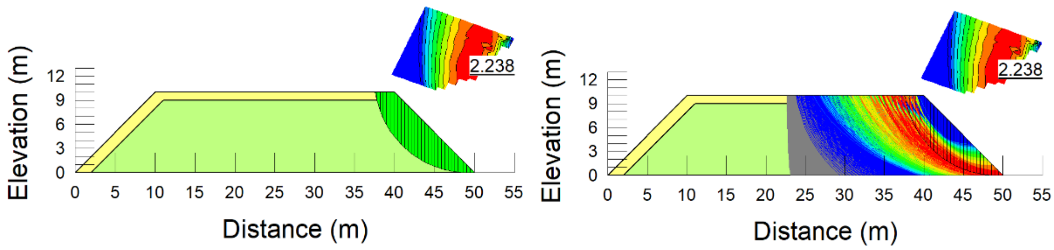

Figure 9. (a) critical surface and (b) factor of safety map for the landfill scenario

4 Conclusion

This paper presented the investigation of a clayey sandy soil that is being used as a cover layer of the MSW landfill in the municipality of Altinho-BR.

Based on the investigation of the compacted soil strength it was observed that the soil presented an expected friction angle for a sandy soil. On the other hand, the cohesion result, despite presenting a composition of 16% of clay and 10% of silt, was equal to 56.6 kPa; this is a value above the expected for a soil with 69% of sand.

From the numerical modeling of slope stability, it was observed that the soil deposit, which is being mined in the field, is stable with FS = 3.1, as well as the landfill cell, which presented a FS = 2.2.

Finally, this study highlights the importance of investigating the slope stability in landfill scenarios, not only for the landfill cells but also for the soil deposit that is being mined. Therefore, the safety of workers who are laboring in mining activities, as well as in the landfill execution and monitoring will be guaranteed.

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