Determination of Shear Strength Parameters of Municipal Solid Waste (MSW) by Means of Static Plate Load Tests

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ABSTRACT

Stability analysis for MSW landfills is based on limit equilibrium methods of general use in Geotechnics, in spite of the fact that rheological behavior of MSW is different from that of typical soils: stress-strain curves show an increase of strength without the occurrence of failure within the normal range of strain levels of shear strength tests, and shear strength and deformability parameters alter along time. Furthermore, there is the additional problem of the representativeness of waste samples for laboratory tests. This paper proposes to evaluate strength parameters of MSW by means of in-situ static load plate tests carried out in a sanitary landfill in the metropolitan region of Sao Paulo, Brazil, and Terzaghi´s formulation for ultimate bearing capacity of direct shallow foundations. Cohesion-friction angle curves for different strain levels obtained by analysis of in-situ tests are presented and discussed.

INTRODUCTION

In Brazil there is an on-going trend to centralize municipal solid waste (MSW) landfills due to the scarcity of adequate available sites near the urban areas of big cities. For municipalities with less than 20,000 inhabitants, establishment of inter-municipal MSW landfills allows a shared management and a better usage of the expensive necessary infrastructure. As a result, sanitary landfills have become voluminous structures with heights sometimes reaching dozens of meters. Stability analyses are fundamental for the safety of these landfills, inasmuch as they are often located near inhabited areas, freeways, and others spaces of public or environmental interest.

Stability analysis of MSW landfills is based on the assumption that MSW failure may be represented by a Mohr-Coulomb envelope and carried out using limit-equilibrium slope stability methods traditionally employed in Geotechnics. The approach of limit-equilibrium methods is to analyze the conditions that would exist at collapse, and to apply suitable safety factors to prevent it; slope movements are often of no concern as long as there is assurance that even larger motions will not suddenly occur (Lambe & Whitman, 1979).

In practice, a proposed slope configuration is analyzed considering that the composing materials are rigid-plastic, i.e. a sliding mass will be separated from the original slope without previous deformation, and that static momentum and force equilibrium applies to the mass in the imminence of sliding. The mobilized resistance (i.e. shear stress required for equilibrium) is compared to the shear strength of the soil to evaluate the safety factor; if the latter does not meet the required value, an alteration in the slope configuration is necessary. Some well-known methods (Fellenius, Simplified Bishop, Spencer, Janbu, among others) are generally available in commercial stability analysis softwares for geotechnical design.

However, geo-mechanical properties of MSW, particularly the rheological behavior, are significantly different from those of typical soils. Stress-strain curves obtained from triaxial compression tests (Manassero et al., 1996; Vilar et al., 2006) and field observations have shown a monotonic increase of stress as a function of imposed strain, without the evidence of a peak failure or a trend for an asymptotic value of stress for the range of strains applied by laboratory equipments. Failure deviator stresses which account for the evaluation of the cohesion and friction angle of MSW are generally related to an acceptable level of strain.

An additional problem in the evaluation of MSW strength parameters is the lack of representativeness of collected samples when compared to the usual dimensions of geotechnical laboratory equipments of current use. Large-scale laboratory equipments have been used (Carvalho, 1999; Zekkos et al.. 2010) to allow for more representative samples, and back-analyses of failures in MSW landfills have yielded data based on the overall waste mass behavior (Benvenuto & Cunha, 1991; Bouazza & Wojnarowicz, 1999). This paper proposes to apply in situ tests carried out in a large sanitary landfill to contribute to the evaluation of shear strength parameters of MSW.

Shear strength parameters of MSW

Shear strength parameters of MSW vary significantly in the literature: cohesion ranges from 0 to 60 kPa, whereas there are reported values of friction angle from 18º to 49º. Besides MSW composition, age and compaction, the method of evaluation also affects the measured values (Boscov & Abreu, 2000); furthermore, it is not always stated if these values refer to total or effective parameters. Some designers proceed to stability analysis combining high effective parameters with elevated pore pressures, whereas others prefer to deal with total parameters.

Back-analysis of slope failures in two large landfills in the metropolitan region of Sao Paulo, Brazil, yielded values of shear strength parameters closer to the minimum values presented in the literature (Tables 1 and 2). Both landfills received approximately 8,000 tons of MSW per day and were designed and operated according to international specifications; however, the failure in Bandeirantes Sanitary Landfill occurred in an older part of the landfill that did not meet requirements for drainage. Some designers have been contesting these values and suggesting the adoption of higher parameters, however without sufficient scientific basis.

Azevedo et al. (2006) carried out laboratory plate tests in a large dimension lisimeter (1.0 m of diameter and 1.6 m of height) in order to determine shear strength parameters of MSW by means of Terzaghi's bearing capacity formulas for direct shallow foundations. The wood slab used in these tests had 16.0 cm of diameter and 40.0 cm of height. MSW was compacted to the unit weight of 7.0 kN/m³ and subjected to 17 loading stages of 24 hours. The authors concluded that the measured shear strength parameters were significantly smaller and the strains were higher than those obtained by means of triaxial tests.

Table 1. Shear strength parameters of Bandeirantes Sanitary Landfill obtained by back-analysis of slope failure in 1991 (Kaimoto & Cepollina, 1996).

Waste age	Cohesion (kPa)	Friction angle (º)
Old waste	13,5	22,0
Waste older than 2 years	16,0	22,0
Recent waste (less than 2 years old)	16,0	28,0

Table 2. Shear strength parameters of Sitio Sao Joao Landfill obtained by back-analysis of slope failure in 2007 (Ecourbis Ambiental S/A, 2007).

Waste age	Cohesion (kPa)	Friction angle (º)
Old waste	19,0	28,0
Recent waste	13,5	22,0

The method proposed by Azevedo et al. (2006) was used in this research to determine shear strength parameters of MSW by means of static plate load tests carried out in a large sanitary landfill in the metropolitan region of Sao Paulo. Therefore, Terzaghi's bearing capacity equations for direct shallow foundations and the principles of static plate load test principles will be briefly presented as follows.

Bearing capacity of direct shallow foundations

The evaluation of the bearing capacity (force or stress that causes failure of a soil mass due to the application of a load over a finite area on the surface of the subsoil) of strip footings was developed by Karl Terzaghi in 1943. The solution was based on the assumptions of rigid-plastic behavior for the soil, validity of forces equilibrium at the imminence of failure, that the resistance offered by the weight of the soil and by the surcharge can be evaluated independently of each other, and a particular failure configuration.

$$Q_r = 2\,P_p + 2\,B\,c\ \mathrm{tg}\varphi - \gamma\,B^2\ \mathrm{tg}\varphi$$

Q_r: bearing capacity of a strip footing
P_p: passive thrust
B: half of the footing width
c: soil cohesion
φ: soil friction angle
γ: soil unit weight

Initially three ideal conditions were studied: non cohesive soil, footing base on the subsoil surface and weightless soil. In order to meet real conditions (cohesive soil, embedded footing and weighty soil), bearing capacity factors were added to the equation. Furthermore, shape correction factors were included to account for isolated footings. The following equation expresses the bearing capacity of a circular footing, whose base is located at a depth D below ground surface, over a cohesive soil.

$$q_r = 1{,}3\ cN_c + q_0 N_q + 0{,}3\ \gamma\ B\ N_\gamma$$

q_r: bearing capacity of a circular footing
N_c, N_q and N_γ = bearing capacity factors
$q_0 = \gamma D$
D: depth of the footing base
γ: soil unit weight
B: footing diameter

Plate load tests

Plate load tests are used in foundation engineering to determine the allowable bearing stress and the stress-strain behavior of the soil under a shallow foundation, as they simulate the load application of a footing on a soil layer. If the test reaches shear failure, it is possible to determine the applied load that induces a shear stress equal to the soil shear strength. Very frequently, however, physical failure does not occur, and it is necessary to adopt a failure criterion. A common criterion is to consider as ultimate load that corresponding to a deformation of 10% of the plate diameter. Brazilian standard ABNT NBR 6489-84 considers as allowable bearing stress the lowest between q_{10} e ½ q_{25}, respectively, stresses correspondent to settlements of 10 mm and 25 mm; practical evidence indicates that the latter condition is always more critical than the first (ABMS/ABEF 1996). Failure may not be reached by many reasons, such as site conditions, costs, time schedule, and insufficiency of the reaction, load or measuring systems.

When submitted to the applied load, the soil mass underlying the plate may present very large settlements; volumetric reduction accounts for the majority of the total deformation. This behavior is generally related to soils of low resistance such as soft clays and loose sands. Compressible soils do not present significant lateral deformation (little if any surface heaving occurs) and practically do not transfer efforts to the rest of the soil mass apart from the plate. Puncturing failure of the plate is not perfectly defined and does not develop in the entire soil mass, but is restricted to the proximity of the load application; hence the denomination of local failure.

In resistant soils such as stiff clays and compact sands, load causes shape alteration, i.e. compression in one direction provokes expansion in the transverse direction. Settlements induce lateral deformation which is transmitted instantaneously to the rest of the soil mass, causing a well defined failure that reaches the soil not just under the plate; that is known as general failure.

Stress distribution under a plate has already been well studied. Generally the region of interest regarding stress spreading is the portion of the soil mass where the induced stresses in the subsoil are equal or greater than 10% of the stress applied by the plate or foundation base. Stresses lower than 10% are considered negligible for practical foundation design. The region under the base where significant stresses (i.e. >10% applied surface stress) are induced in the subsoil is called stress bulb, which reaches generally 1.5 to 2 times the width of the loaded area.

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EXPERIMENTAL INVESTIGATION

CGR Itapevi (Itapevi Waste Management Center) is an enterprise located about 42 km of the city of Sao Paulo and attends 8 municipalities on the west side of Sao Paulo metropolitan region. One of its units is a landfill, which has been operating since April 2003, certified for 1,200 tons per day of MSW in co-disposal policy with no hazardous industrial waste. The enterprise has 205,546 m² of area with 100,180 m² to landfill operation. The landfill volumetric capacity is 3.2 million tons of domiciliary, commercial and no hazardous industrial waste.

In situ plate load tests followed ASTM D1194–94 and Brazilian standard ABNT NBR 6489-84. Test locations were selected with a view to measuring parameters of recently deposited and compacted MSW. Initially the soil cover of nearly 40 cm was removed. A circular steel plate of 80 cm diameter was used. Loads were applied by a hydraulic jack assembly reacting against a truck carried with crushed stone, constituting a loading platform of almost 30 tf. This solution was less expensive and safer than reacting against a platform fixed by anchor rods because of the low strength of the subsoil.

The usual criterion for load increment which is the stabilization of the settlements of the anterior stage was not followed due to the high compressibility of the waste mass; instead a criterion of 30 minutes of load application was adopted. Three dial gages measured plate settlements with accuracy of 0.01 mm. The uniform distribution of the load was to be guaranteed by the ball and socket joint, but the heterogeneity of the soil mass caused different responses in the three dial gages, as shown in Figure 1.

Settlements were measured after 1, 2, 4, 8, 15 and 30 minutes after the application of each 3-tf load increment. Reaching failure was not attempted. Tests were carried out till a total settlement of at least 10% of the plate diameter was reached. Limiting factors to complete the test were the weight of the truck and the tilting of the plate. Heavier trucks would show more important subsidence under the tires, which would affect the analysis of results. On the other hand, tilting was a consequence of the subsoil heterogeneity; the application of a momentum to level the plate would represent an unacceptable interference in test results.

RESULTS

The results of three plate load tests were used for the determination of MSW strength parameters (trenches 1, 2 and 3). Figure 1 exemplifies the obtained curves of settlement as a function of the applied load. It can be observed that differences among the measurements of the three gages are remarkable when compared to tests carried out in soils.

For each test, an average curve of vertical strain as a function of applied stress was determined (Figure 2). Strain was calculated as the settlement divided by twice the plate diameter. Differences among the three tests are also significant when compared to tests carried out in soils. Trenches were excavated in MSW of same age and compaction, however randomly selected in order to observe heterogeneity of MSW mass.

For strains equal to 1.25%, 2.50%, 3.75%, 5.00%, 6.25% and 7.50%, values of friction angle of 5^o, 10^o, 15^o, 20^o, 25^o, 30^o and 35^o were applied to Terzaghi´s equation of bearing capacity of circular footings in order to calculate values of cohesion that would result in the corresponding measured stress values. Results are shown in Figures 3, 4 and 5 for trenches 1, 2 and 3, respectively.

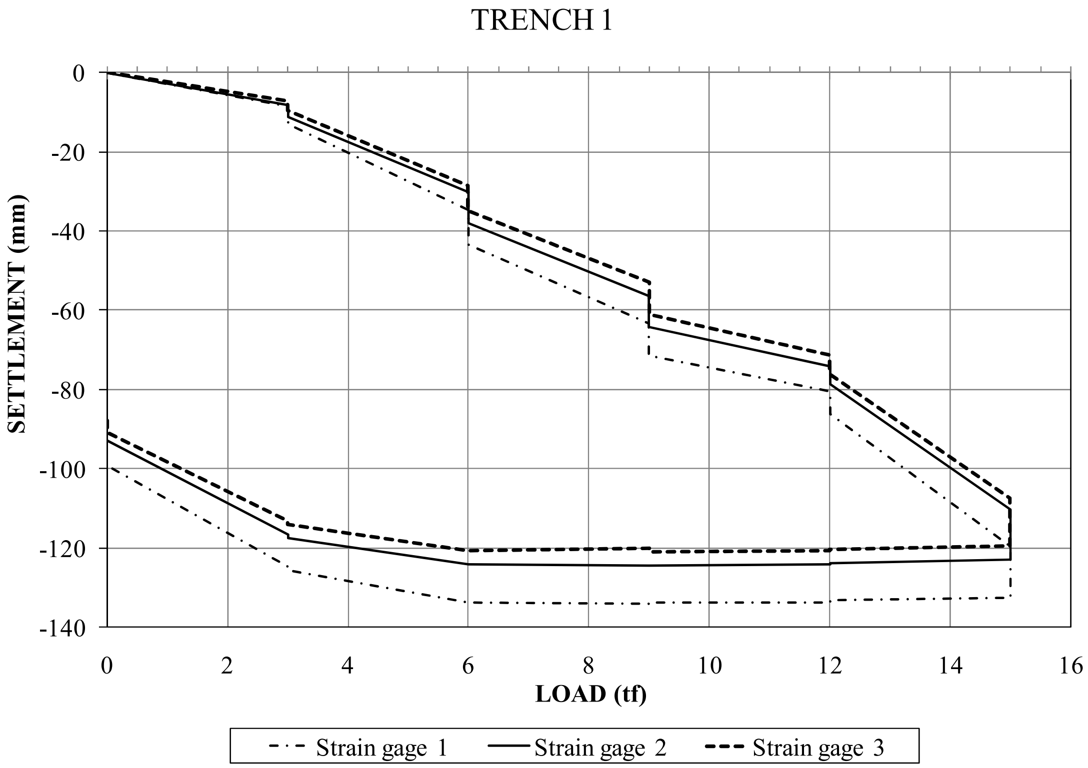

Figure 1. Results of plate load test in trench 1.

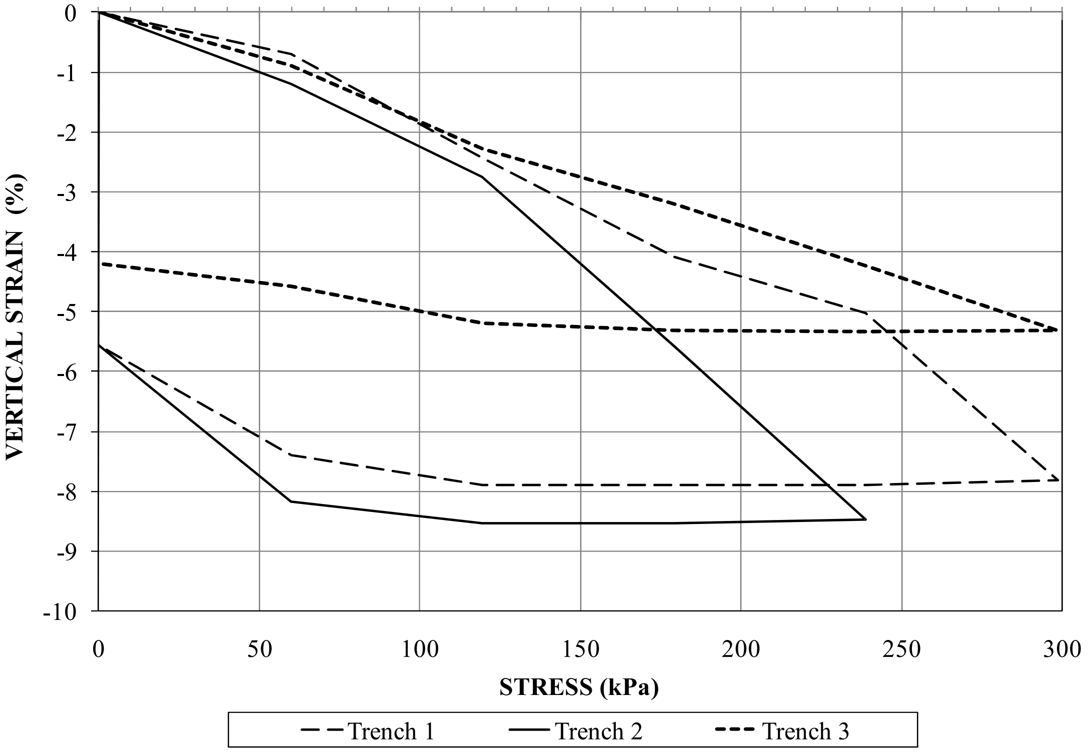

Figure 2. Stress-strain curves for trenches 1, 2 and 3.

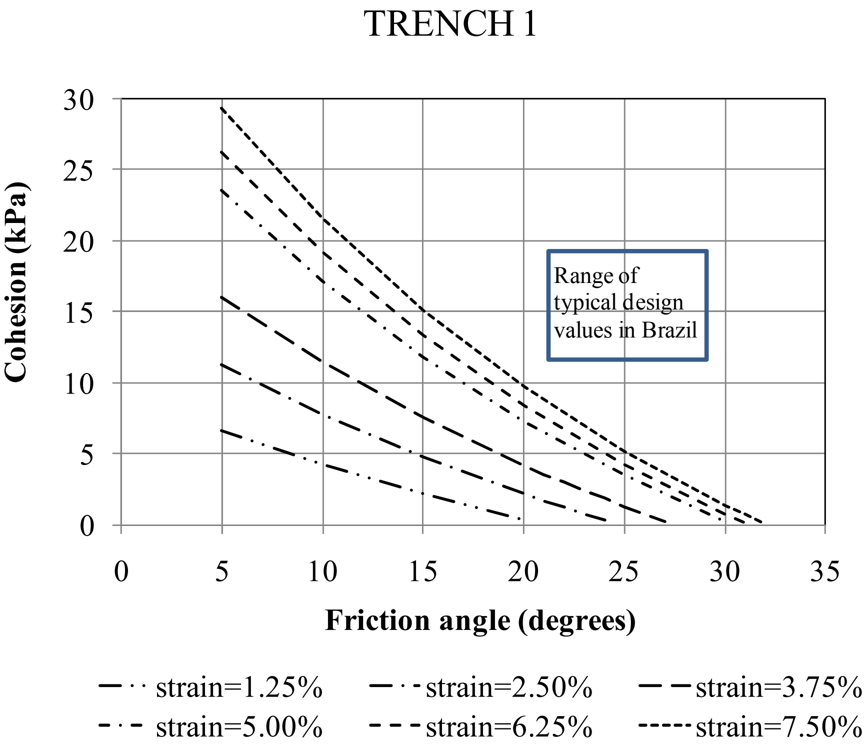

Figure 3. Cohesion and friction angle for trench 1.

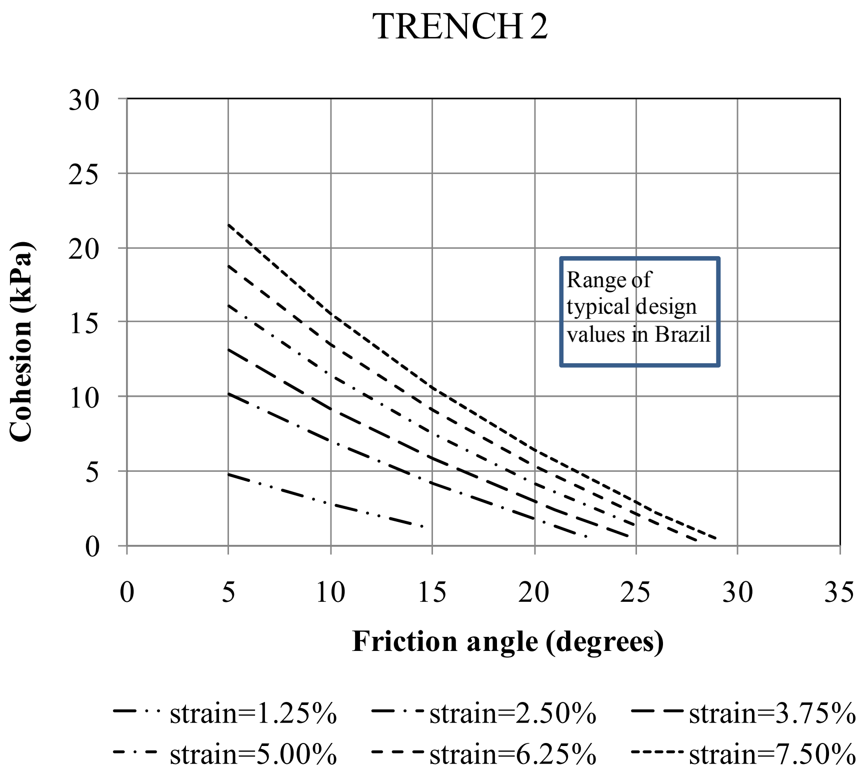

Figure 4. Cohesion and friction angle for trench 2.

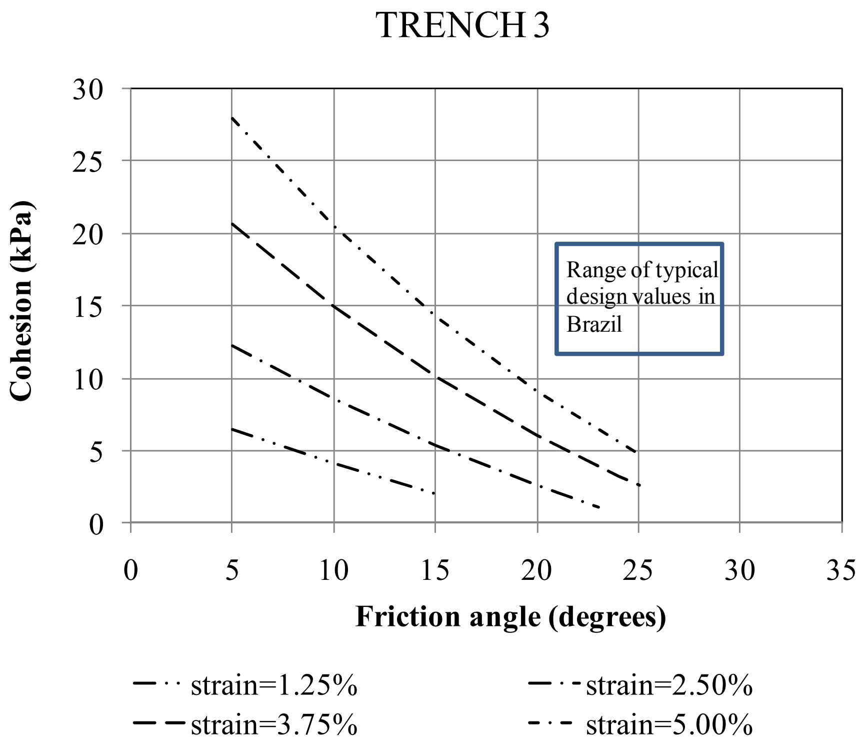

Figure 5. Cohesion and friction angle for trench 3.

Apart from slight differences among the three tests, it can be concluded that cohesion values range from 5 to 30 kPa whereas the friction angle varies from 5 to 30^o. For a friction angle between 22 to 28^o, which is the usual range of design values, cohesion would be limited to 8 kPa, much lower than common design practice (16 to 19 kPa for recent waste, 13.5 kPa for old waste). Roughly extrapolating calculated cohesion for 10% strain, values of 3 to 19 kPa would be reached for friction angles varying from 20 to 30^o (Figure 6).

Azevedo et al. (2006) had already observed that strength parameters obtained by plate tests are lower than those measured in triaxial tests. Samples employed in laboratory tests, even in large scale equipments, tend to be more homogeneous than in situ waste. Moreover, a previous removal of larger particles is necessary. Confining stresses have also to be selected based on the designer´s assumptions of waste mass stability. The region affected by the plate test, of approximately 1.5 m depth, tends to be more representative of the overall MSW mass, as well as confining stresses and lateral confinement.

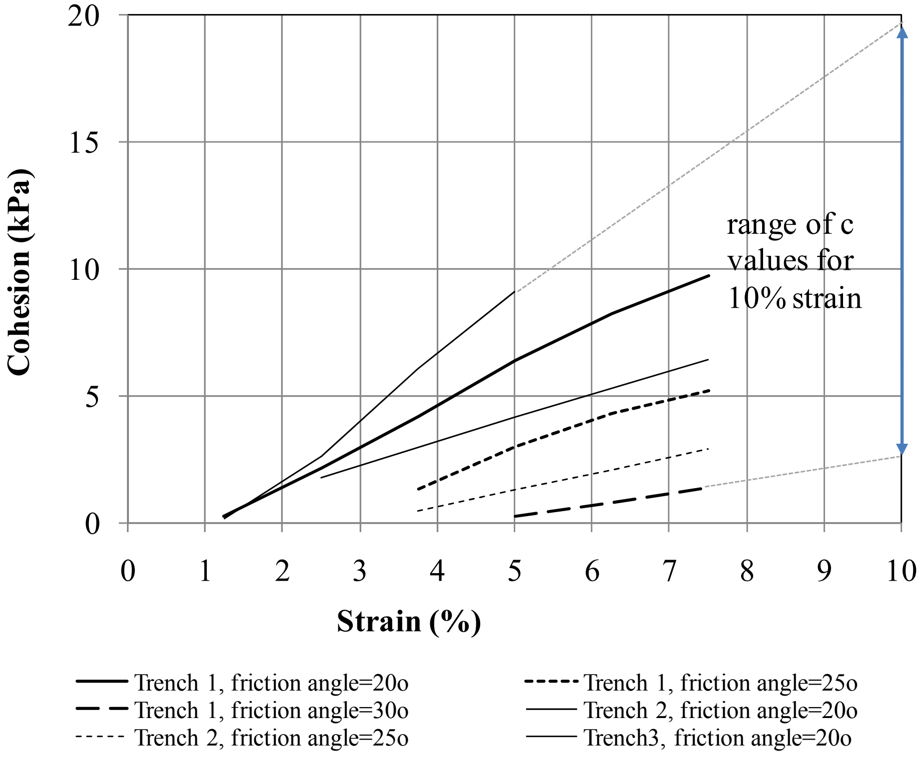

Figure 6. Estimated cohesion values for 10% strain.

CONCLUSION

Load plate tests in MSW landfills have some physical limitations mostly due to the material heterogeneity and compressibility, so that failure or even very large deformations may not be reached. On the other hand, the loaded region and the confining stresses are much more representative of the overall waste mass than in laboratorial triaxial tests. Values of cohesion and friction angles as a function of vertical strain thus obtained, despite being lower than those measured in laboratory, are probably more accurate. This paper indicates values of cohesion not higher than 10 kPa for friction angle varying from 20 to 30°, for strains of 5.0 to 7.5%. Cohesion as high as 19 kPa could be mobilized for 10% strains.

ACKNOWLEDGEMENTS

The authors would like to thank FAPESP (Foundation for Research Support of the State of Sao Paulo) for the financial support, ESTRE Ambiental SA in the person of the Engineer Afonso Pazin for the access and help in CGR-Itapevi, and Bureau de Projetos e Consultoria Ltda. for the execution of the tests.

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