Using DMT to Determine Overconsolidation Ratio (OCR) in Compacted Fills

A.C.G. Queiroz, J.C. Carvalho, R.C. Guimarães

Abstract. Quality of compacted fills is essential to the proper functioning of a structure as a whole. Currently, quality control is achieved by testing to determine the deviation of moisture content of recently compacted soil in relation to optimum moisture and degree of compaction reached. Based on the results, deformability, permeability and strength related characteristics are inferred. However, data obtained by using this technique do not always reflect actual behavior of soil, and are only applicable during the construction phase. More elaborate field tests are generally used only when problems are detected at completed landfills, but such tests may also be of great value during execution, since they provide soil geotechnical parameters, thus enabling control based on behavior rather than just physical properties. This study examined the application of correlations developed by several authors for estimating OCR by DMT in compacted fills. The results showed that dilatometer testing (DMT) is a potential tool for control of compaction and should be further studied, particularly in relation to the effects of suction on DMT results.

Keywords: DMT, compacted fills, OCR, suction, correlations, control of compaction.

1. Introduction

In earth dams and road works the quality of compaction of fills is essential for proper performance. In most cases, technological control of compaction is carried out layer by layer, based on moisture and degree of compaction. However, this technique is only applicable during construction and the data obtained do not always reflect soil behavior.

When problems are detected in finished landfills, or those still under construction, but quite high, possible causes may be investigated by bore holes, bell holes or field trials. Although rarely used, these tests may also be useful during construction in order to have compaction control based on the material's behavior. However, few reports cover in-situ investigation of the behavior of compacted fills for validating correlations between results from these tests and geotechnical parameters obtained in laboratories.

Of the field testing methods, DMT may be a good option for examining the behavior of landfills since it is relatively simple to do and provides estimates for soil geomechanical parameters used to predict the behavior of fills such as earth dams.

The parameter selected for this study was the overconsolidation ratio (OCR), based on the belief that it can represent the behavior of compacted soil, while also being directly related to compaction control parameters. Furthermore, in earthworks such as fills used for dams or highway embankments, an important feature is the soil's elastic regime, hence the importance of estimating OCR in these cases.

2. Uses of DMT For Estimating Overconsolidation Ratio (OCR)

The ratio between maximum effective vertical stress experienced by the soil and the current effective vertical stress is called the preconsolidation ratio (PCR) or overconsolidation ratio (OCR). In the case of compacted soils this is obviously a pseudo preconsolidation ratio, since it reflects only the effects of compaction rather than the effect of actual consolidation as such.

Marchetti (1980) observed a certain similarity between the profiles of horizontal strain index K_D and OCR. Based on data from a non-cemented clay, he proposed Eq. 1, valid for soils in which $0.2 < I_D < 2$, and I_D is material index.

$$\text{OCR} = (0.5K_D)^{1.56} \quad (1)$$

Marchetti & Crapps (1981) reviewed the original approach to develop Eqs. 2, 3 and 4.

$$I_D < 1.2 \quad \text{OCR} = (0.5K_D)^{1.56} \quad (2)$$

$$I_D > 2.0 \quad \text{OCR} = (0.67K_D)^{1.91} \quad (3)$$

$$1{,}2 < I_D < 2.0 \quad \text{OCR} = (mK_D)^{n} \quad (4)$$

where

$$m = 0.5 + 0.17P \quad (5)$$

Angela Custódia Guimarães Queiroz, M.Sc, Doctoral student with the Geotechnical Graduate Program, Universidade de Brasília, Brasília, DF, Brazil, e-mail: eng_angela@yahoo.com.br.
José Camapum de Carvalho, PhD, Professor, Geotechnical Graduate Program, Universidade de Brasília, Brasília, DF, Brazil, e-mail: camapum@unb.br.
Renato Cabral Guimarães, PhD, Professor, Universidade Estadual de Goiás, and engineer with FURNAS Centrais Elétricas S.A., Aparecida de Goiânia, GO, Brazil, e-mail: renatocg@furnas.com.br.
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$$n = 1.56 + 0.35P \quad (6)$$

$$P = \frac{I_D - 1.2}{0.8} \quad (7)$$

Eq. 8 is a suggestion from Lacasse & Lunne (1988) to estimate OCR, and is valid for OCR >1.25.

$$\text{OCR} = 0.225 K_D^m \quad (8)$$

where m = 1.35-1.67, lower value corresponds to high- and higher to low-plasticity soils.

Lunne *et al.*(1989) posed OCR estimates considering age of clay (Eqs. 9 and 10).

$$\text{OCR} = 0.3 K_D^{1.17} \text{ for } S_u / \sigma'_{v_0} \le 0.8 \text{ (young clays)} \quad (9)$$

$$\text{OCR} = 2.7 K_D^{1.17} \text{ for } S_u / \sigma'_{v_0} > 0.8 \text{ (aged clays)} \quad (10)$$

It is noteworthy that the proposals outlined above for determining the OCR were originally created to be applied to clay soils. However, this study used due to the lack of equations for the compacted soils, thereby aiming to evaluate if these adequariam well or need adjustment.

3. Materials and Methods

To conduct the study was selected an area on the left shoulder of the João Leite dam in the municipality of Goiânia (GO), approximately 6.5 km from the state capital. The extensive experimental campaign involved three DMT-type boreholes and digging a pit for removal of deformed and undeformed samples in order to carry out several laboratory tests, such as consolidation, triaxial, and determining the water retention characteristic curve using the filter paper technique. Figure 1 shows plant location of the tests.

This clayish fill was made up from homogeneous residual soils that were plastic (liquid limit over 40%, clay fraction over 20% by weight, obtained with the use of dispersant), not very active, and showed low permeability ($k < 10^{-8}$ m/s) when compacted. Compaction was executed with energy equivalent to Normal Proctor.

The methodology used for laboratory testing followed specifications set by the Brazilian Technical Standards Association (ABNT), the American Society for Testing and Materials, and Furnas Soil Laboratory procedures. Our DMT procedure followed the *Flat Dilatometer Manual* and ASTM D 6635 recommendations.

4. Estimated Overconsolidation Ratio (OCR)

OCR was calculated using correlations proposed by Marchetti (1980), Marchetti & Crapps (1981), Lacasse & Lunne (1988), Lunne *et al.* (1989) for young clays, and laboratory test results (consolidation and k_0 type triaxial). Figure 2 and Table 1 show the findings.

A review of the OCR values obtained with the correlations suggested for dilatometer testing shows that they overestimated this parameter. The equation developed by Lunne *et al.* (1989) is the one that comes closest to laboratory findings, however, the latter were also higher than expected.

Obtaining this parameter in the laboratory consists of just determining the pre-consolidation stress, and for this study this was done using the compressibility curves of the consolidation and K_D triaxial testing type, since geoestatic

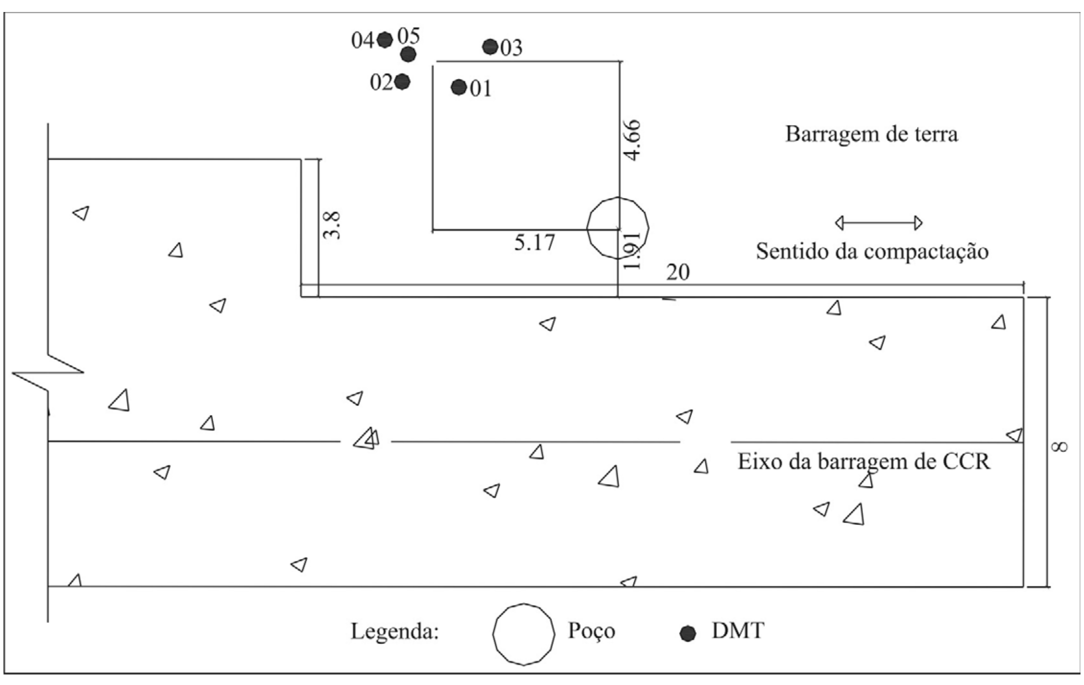

Figure 1 - Plant location of the tests.

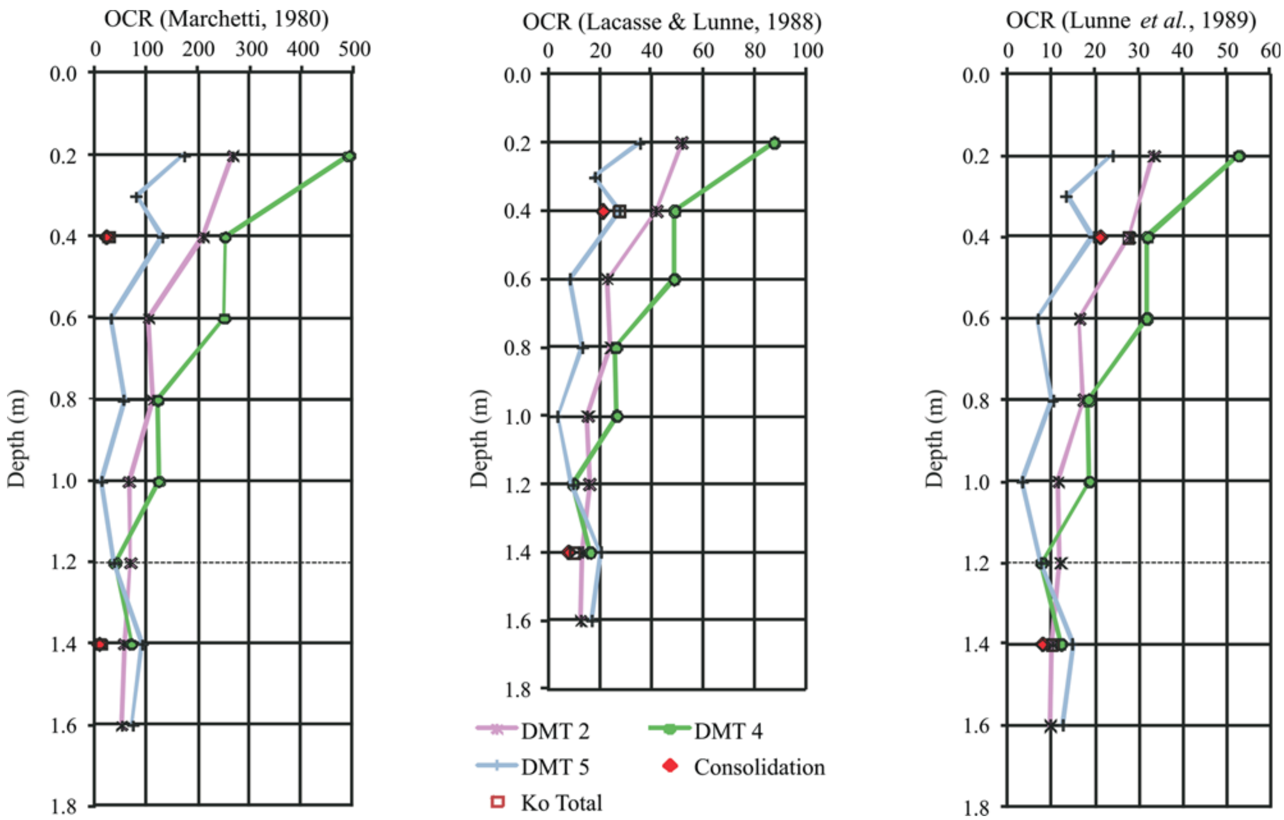

Figure 2 - OCR calculated from oedometric compression testing and DMT.

stress is just calculated. This calculation does not take into account the effects of suction acting on the material and may lead to significant errors in results. Another aspect to be noted is preconsolidation as a result of compaction is affected by aspects such as roller weight, leg shape and size or tire pressure, depending on the situation, and compaction moisture.

Correlations proposed for OCR are based on the dilatometric ratio K_D, which uses a calculated geostatic stress value and excludes suction effects.

Table 1 - OCR calculated using method proposed by Marchetti & Crapps (1981).

Depth (m)	OCR		
	DMT 2	DMT 4	DMT 5
0.2	14856.5	8671.0	5937.8
0.4	756.0	1026.3	598.9
0.6	322.2	250.3	1087.8
0.8	354.2	388.8	164.4
1.0	180.9	396.9	44.3
1.2	192.6	94.6	37.1
1.4	149.4	198.7	271.7
1.6	136.7	-	72.9

Since both laboratory findings and values obtained from correlation proved to be high, and neither took into account suction effects, an analysis including this parameter was conducted to evaluate any effect it might have on results. However, this analysis was only applied to type k_0 triaxial tests and the method proposed by Lunne *et al.* (1989), due to their results being apparently providing a better fit than expected.

Figure 3 shows characteristic curves to water retention related suction matrica a function of moisture obtained for the studied soil.

For the results of the k_0 test, the predetermined consolidation stress was maintained and suction added to geo-

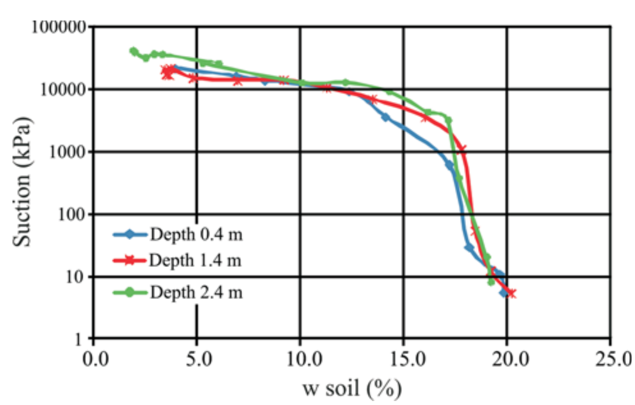

Figure 3 - Characteristic curves as a function of moisture.

static stress, so geostatic stress was then the sum of suction stress and calculated geostatic stress. These suction values were found as follows: with experimentally determined moisture contents corresponding to the depth in question, suction was obtained by reading on the appropriate characteristic curves.

For the results obtained using the method proposed by Lunne *et al.* (1989) K_D values were recalculated using geostatic stress with suction effect. Having obtained these values, new OCRs were determined, as shown in Fig. 4, together with the new laboratory OCRs.

The results obtained considering the suction effect on geostatic stress and consequently on OCR, were substantially better than previous ones. However, the values found up to 0.80 m depth show some scatter. This dispersion may be due to unevenness in compression itself, since for the compressed fill involved has really a pseudo OCR, *i.e.* a state of pre-consolidation induced by compaction which may vary slightly from point to point. The dispersion shown may also be caused by variations in moisture and therefore in suction across testing points. This hypothesis was verified as described below.

An average of the OCR values obtained for the three tests (DMT 2, 4 and 5) was calculated and the values found were almost identical to those for DMT test 2 (Fig. 4). The mean OCR results obtained were matched with the correlation of Lunne *et al.* (1989) for each point in the three tests, and with known p_0, effective vertical stress (σ'_{vo}) was determined. From this amount it was removed the portion of vertical stress due to own weight, thus leaving suction. The following is an outline of the verification:

$$\overline{\text{OCR}} = \text{OCR}_n = 0.3 \cdot k_d^{1.17} = \left[0.3 \cdot \left(\frac{P_0}{\sigma'_{v_0}}\right)^{1.17}\right]_n \therefore \quad (11)$$

$$\sigma'_{v_0} = \sigma'_{VPP} + S$$

where σ'_{vpp} = vertical stress due to own weight, or calculated vertical stress and S = suction.

Using the appropriate characteristic curves (representative of depth) and the suctions obtained, the corresponding moistures were found. Figure 5 shows moisture content values determined directly in the laboratory and those found via the characteristic curve, and also deviations between them.

Figure 5 shows that the moisture values found using the characteristic curve are very close to the laboratory values, with a maximum deviation of 1.45%. This means that OCR estimated by DMT does reflect the material's properties. Note also that the results are more scattered in the range up to 0.8 m depth, as are the OCR results, which confirms the initial hypothesis that OCR variation is mainly due to moisture variations.

Since the moisture results obtained using characteristic curve were satisfactory, the same methodology was applied to obtain the degree of saturation, but this time using

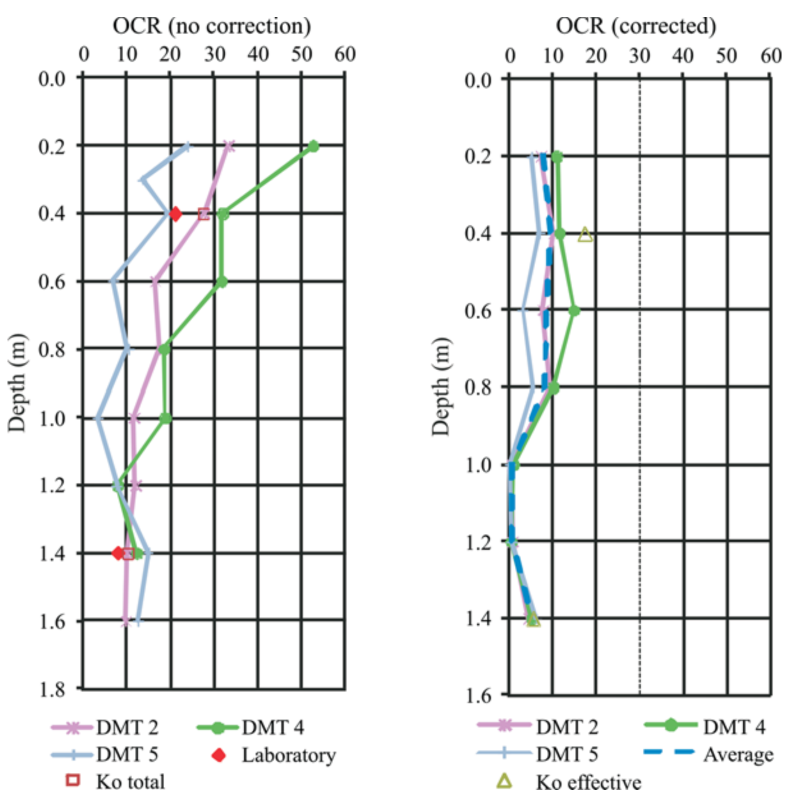

Figure 4 - OCR values calculated with and without the effect of suction.

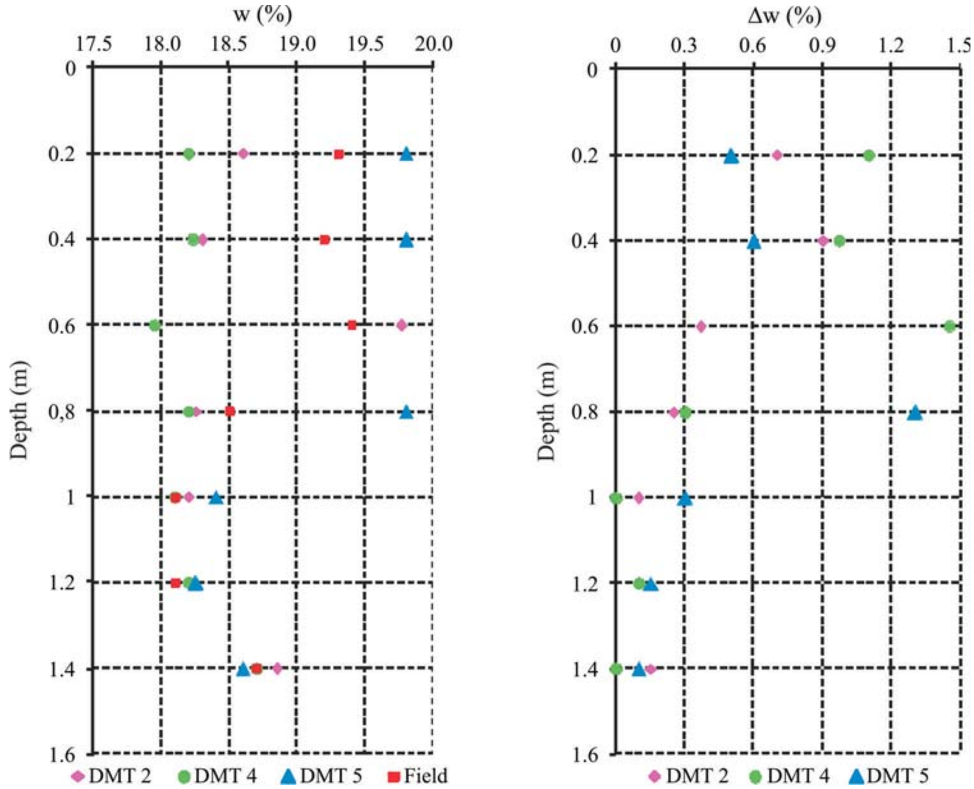

Figure 5 - Moisture values obtained in the laboratory and those found using the characteristic curve, and deviations of moisture (in module)

the characteristic curves depending on the degree of saturation. The main aim of this procedure was to determine the void ratio and therefore specific dry weight and degree of compaction.

Knowing the degree of saturation, four different void index profiles were determined for each test point, thus for each profile using moisture values obtained in different ways. The first used the moisture values found from characteristic curves (e_{cc}), the second the average of the latter ($e_{cc\ average}$), the third laboratory values ($e_{bellhole}$) and the fourth, the average of the latter ($e_{bellhole\ average}$). This artifice was used in an attempt to find the values showing the best fit with those calculated conventionally. Figure 6 shows the average of the results obtained.

Void ratios determined using the degree of saturation obtained from the characteristic curve and those calculated conventionally show a good fit down to 0.80 m depth, *i.e.* in the range where the curve used corresponded to the level altimetry 710,400 m. From this point, indices determined using the new method diverged considerably from those found by the conventional method. This was due to problems in determining void ratios during the filter paper test for this depth, leading to unrepresentative results for the soil studied.

Void ratios found for different soil moisture conditions were not greatly different, but the profile using moisture obtained from the characteristic curve proved to be a better option. Therefore the determination of this parameter would be based on the DMT results and the characteristic curves. However, the void ratio determination also requires the real specific weight of grains, but a correlation between this and the dilatometer test could be studied subsequently in order to optimize the process.

Having determined void ratio, and having obtained maximum dry density for the material studied, dry density and degree of compaction (DC) was calculated. Figure 7 shows the values obtained for degree of compaction.

The values of the degree of compaction wee consistent and agree with each other and with those obtained in the laboratory up to 0.80 m depth. What happens after that is due to problems in executing the filter paper test, as explained above. The behavior obtained was as expected, since the degree of compaction reflected the void ratio. Generally, however, it was found that using DMT to determine the degree of compaction may be a good alternative, since errors found up to 0.80 m depth were less than 1%, as shown in Table 2. Equation 11 was used to define percentage error.

$$\text{Error}(\%) = \frac{\text{DMT} - \text{Laboratory}}{\text{Laboratory}} \times 100 \qquad (12)$$

Strength and deformability parameters being known, compaction control based soil-behavior may be executed. However, the usual practice for this control is based on dry density and therefore the degree of soil compaction, since

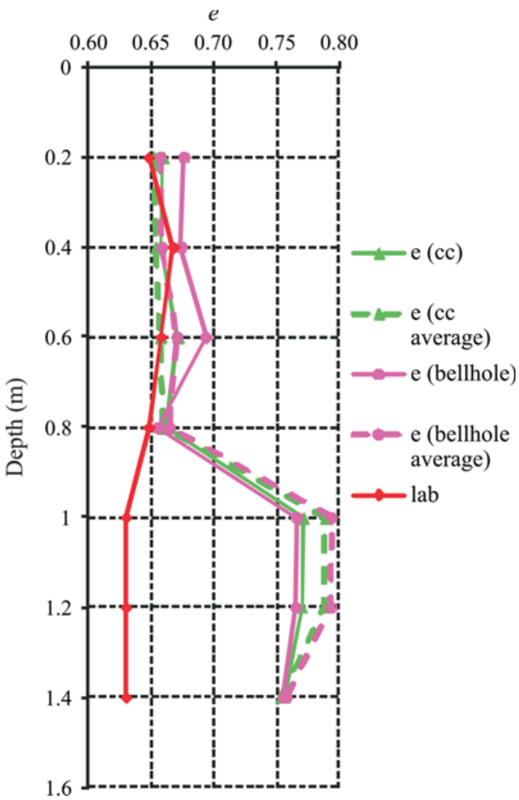

Figure 6 - Void ratios obtained for different soil moisture conditions.

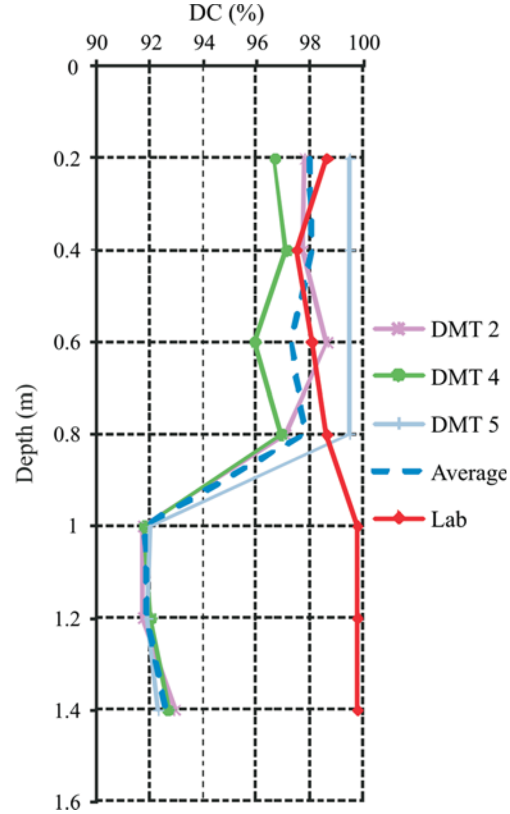

Figure 7 - Degree of compaction.

this means that liberation of the compacted layer is executed in accordance with predetermined limits, and does not require more accurate analysis. This control procedure does not faithfully represent fill properties and behavior. Therefore, there is a crucial need for a method that will control compaction by providing both geotechnical parameters and determining the degree of compaction, which is what the dilatometer test may do.

An important point to consider is that inserting the dilatometric flat in soil leads to compaction of the area around the membrane, and along with reduced void ratio, moisture tends to migrate (Camapum de Carvalho, 1985). Both of which contribute to boost suction. Together with the reduction of void ratio and moisture content there is an increase in the degree of saturation, causing suction to vary. However, there is no way of a priori indication whether it will increase or decrease irrespective of the soil and the characteristic curve shape itself.

Therefore, although the results shown point to the possibility of using the dilatometer test in compacted soils, it is essential to appraise the effect of dilatometer penetration on densification and water migration in different types of compacted soil. Another need is to have well-defined characteristic curves, knowing point-to-point void ratio and moisture content, thus enabling more precise definition of e.pF *vs.* degree of saturation curves proposed by Camapum de Carvalho & Leroueil (2004).

Table 2 - Percentage error – laboratory degree of compaction values and average using DMT.

Depth (m)	Error (%)
0.2	-0.7
0.4	0.6
0.6	-0.8
0.8	-0.8
1.0	-8.0
1.2	-7.9
1.4	-7.2

5. Conclusions

OCR estimates made using the dilatometer test proved superior to those found by laboratory testing. However, laboratory results were also high. Therefore an accurate analysis was performed considering the effects of suction on this parameter, obtained by both the k_0 type triaxial and the proposal of Lunne *et al.* (1989), which produced much more consistent values, thus highlighting the importance of suction when evaluating the mechanical behavior of compacted solids.

However, the results still showed some dispersion, and another aspect emerged on attempting to explain this:

moisture variations were causing dispersion of OCR values and based on the latter, by a retrospective analysis combined with characteristic curves, the soil's void ratios may be determined and hence its degree of compaction.

Dilatometer testing, together with the plotting of characteristic curves representing the loan area used, could provide a good means of controlling compaction of fills for dams, based on soil behavior. Using this technique for highway fills would be somewhat more complicated, since borrow areas move frequently and an excessive flow of tests could be generated.

Control of landfill compaction must be combined with rational use of borrow area, since soil alteration profile strongly affects mechanical and hydraulic behavior.

A point to note is that our comments herein are based solely on testing in just one location. Further research on different types of soil and compaction is needed to develop methodology applicable to compacted soils in general.

References

ASTM (2001) Standard Test Method for Performing the Flat Plate Dilatometer, D 6635-01. West Conshohocken, Pensilvânia, USA, 15 pp.

Camapum de Carvalho, J. (1985) Etude du Comportement Mecanique d'une Marne Compactee. These, nº 9, l'Institut National des Sciences Appliquees de Toulouse, Toulouse, 181 pp.

Camapum de Carvalho, J. & Leroueil, S. (2004) Curva característica de sucção transformada. Solos e Rochas, v. 27:3, p. 231-242.

Lacasse, S. & Lunne, T. (1988). Calibration of Dilatometer Correlations, Proc. ISOPT-1, Orlando, Florida, v. 1, pp. 539-548.

Lunne, T.; Lacasse, S. & Rad, N.S. (1989) SPT, CPT, pressuremeter testing and recent developments on in situ testing of soils. General Report Session. 12th International Conference of Soil Mechanics Foundation Engineering, Rio de Janeiro, pp. 2339-2404.

Marchetti, S. & Crapps, D.K. (1981) Flat Dilatometer Manual. International Report of GPE Inc., Gainesville, Florida.

Marchetti, S. (1980) In Situ Tests by Flat Dilatometer. Journal of Geotechnical Engineering, ASCE, v. 106:GT3, p. 299-321.