Dilatometer Tests for compaction control purposes

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ABSTRACT: DMT was intensively used for compaction control during the landfill execution for a logistic site close to São Paulo – Brazil. The volume involved at the earthwork is around 1,000,000 m³ and 65 DMT soundings were done in the compacted fill, accumulating more than 1,000 m of DMT results. The rigorously controlled landfill was evaluated during its construction process, as it gained height, with monthly DMT campaigns. The results of these tests showed that the first 1.5 m of the landfill height are more susceptible to deformations, even with a rigorous compaction control. The results also indicated that an adequate compaction control can reduce the deformability of the compacted fill by half, when compared to other results of DMT performed in a nearby site, at the same city, but without a rigorous compaction control on the landfill.

Keywords: DMT; compaction control; compacted fill; deformability.

1. Introduction

For the implementation of a logistic distribution park in the city of Cajamar, located near São Paulo, Brazil, the cut volume and fill volume estimated in the earthwork project was around to 1,000,000 m³.

Fig. 1 presents a 3D model of this site, obtained by drone images during the earthwork services.

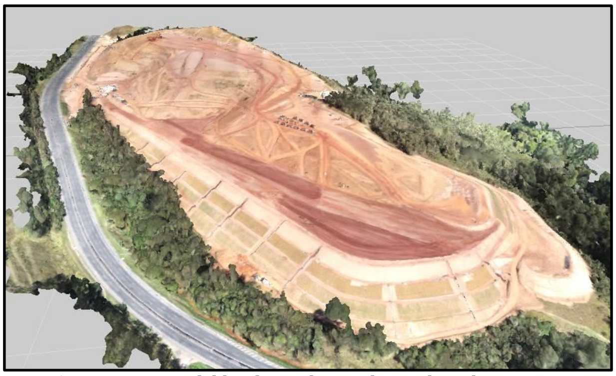

Figure 1. 3D model by drone during the earthwork services.

Considering that the landfill height reached up to 30 meters and a future implementation of heavy structures over them, a rigorous compaction control of the soil to be launched over the natural ground was required, in order to avoid excessive deformations eventually caused by the loads from the operating building.

Therefore, this landfill was executed in layers of only 20 – 25 cm. The acceptance criteria was degree of compaction superior to 98% of standard Proctor, for each layer, measured by Hilf tests performed in different points of the fill.

During the earthwork, a huge campaign of soil sampling was executed in the landfill, in order to determinate its grain size and its compaction curve (standard Proctor).

In the most productive phase, the construction counted with daily standard Proctor tests, which resulted in a big data of maximum dry density and optimum moisture content, called in this work by "optimum points".

The grain size distribution of the soil used in the landfill is presented in Fig. 2, recording the predominance of silty sand with a little clay.

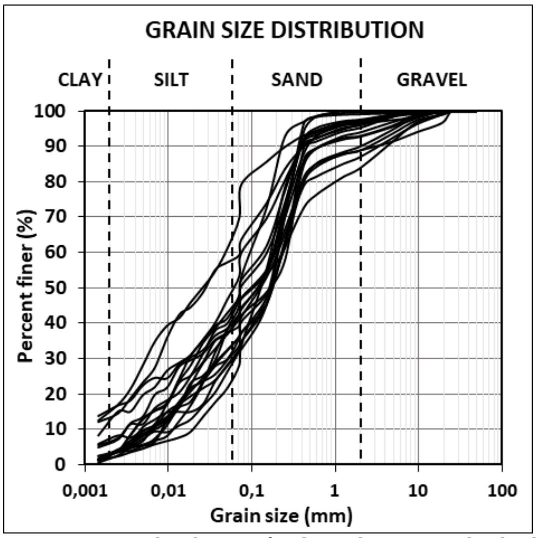

Figure 2. Grain size distribution of soil sampling executed in landfill.

Fig. 3 presents the dispersion of the "optimum points" obtained in situ and the Kuczinski [1] hyperbole, which indicates an empirical equation to the "optimum points" of Brazilian soils.

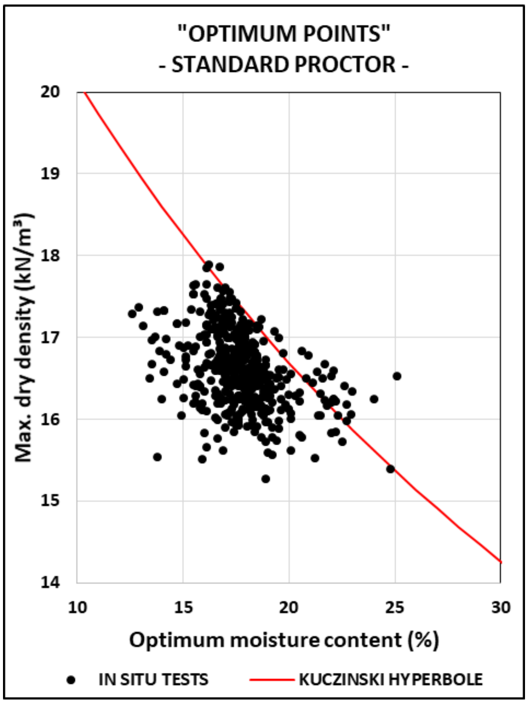

Figure 3. Dispersion of the "optimum points" obtained in the tests.

The most part of maximum dry density values ranged from 16.0 kN/m³ to 17.5 kN/m³ and of optimum moisture content from 16.0% to 19.5%.

Complementarily, this landfill was evaluated during its construction process, as it gained height, with monthly DMT campaigns. The goal was to verify its behavior based on the variation of "P_0", "I_D", "K_D" and "M" obtained in compacted soil layers. When the earthwork was concluded, 65 DMT soundings had been executed and about 50 of them, executed in the fill area, were used in this research.

Those tests were compared to other DMT results performed in a nearby site, at the same city, using the same type of soil for the landfill execution. Its compaction, however, was done without a strict compaction control.

2. Dilatometer test - DMT

2.1. General features

The dilatometer is a stainless steel blade equipped with a circular membrane on one side. The blade is driven vertically into the soil and in every 20 cm a test is perfomed by inflating the membrane and taking pressure readings at prescribed horizontal displacements.

The penetration is done with the aid of pushing rigs adapted from those used in the CPT. The test is compatible with a wide variety of soils (clay, sand, silt and even soft rock).

After the readings corrections, related to the equipment calibration, the test provides the pressures P_0 (at which the membrane starts to expand) and P_1 (pressure required to move the centre of the membrane by 1.1 mm against the soil), as shown in Fig. 4.

These pressures (P_0 and P_1) are subsequently used for interpretation of DMT results in the assessment of soil parameters.

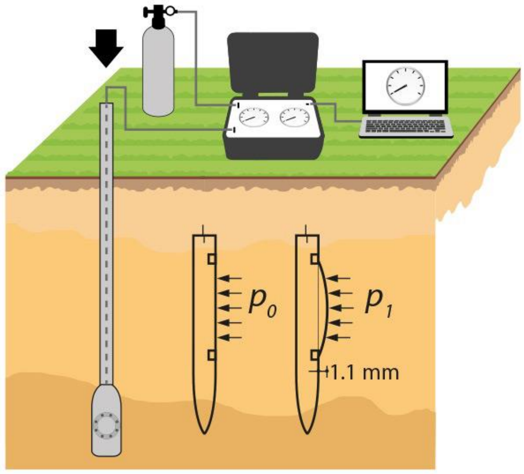

Figure 4. Schematic representation of the dilatometer test.

2.2. Intermediate DMT parameters

Based on the pressures P_0 and P_1, Marchetti [2] defined three index parameters to interpret the test: material index, horizontal stress index and dilatometer modulus.

2.2.1. Material index – I_D

Marchetti [2] observed that the difference between P_0 and P_1 is small for clayey soils and larger for sandy soils.

So he expressed the material index by Eq. (1).

$$I_D = \frac{P_1 - P_0}{P_0 - \mu_0} \tag{1}$$

where μ_0 = pre-insertion pore pressure.

According to Marchetti [2], the soil type can be identified as follows:

- Clay → $0.1 < I_D < 0.6$
- Silt → $0.6 < I_D < 1.8$
- Sand → $1.8 < I_D < (10)$

The material index provides a reasonable estimate of soil type, but not exact in granulometry. Therefore, the parameter I_D is related to the mechanical behavior of the soil and not its real grain size.

2.2.2. Horizontal stress index – K_D

The horizontal stress index (K_D) can be regarded as the coefficient of earth pressure at rest (K_0) amplified by the penetration of the blade. It's expressed by Eq. (2).

$$K_D = \frac{P_0 - \mu_0}{\sigma'_{v0}} \tag{2}$$

where σ'_{v0} = pre-insertion overburden stress.

According to Marchetti [2], in genuinely NC clays (normally consolidated clays) the value of the horizontal stress index is $K_{D,NC} \approx 2$.

2.2.3. Dilatometer modulus – E_D

The value of ($P_0 - P_1$) can be converted into a modulus of elasticity of the soil using the theory of elasticity. Marchetti [2] proposed a solution to this problem by assuming that the space surrounding the dilatometer is formed by two elastic half spaces, in contact along the plane of symmetry of the blade.

For an elastic half space with Young's modulus E and Poisson's ratio υ, when zero settlement is computed externally to the loaded area, it has Eq. (3).

$$S_0 = \frac{2D\,(P_1 - P_0)}{\pi}\frac{(1-\upsilon^2)}{E} \tag{3}$$

For the membrane diameter D = 60 mm, displacement S_0 = 1.1 mm and ratio $\frac{E}{(1-\upsilon^2)}$ defined as E_D, it has Eq. (4).

$$E_D = 34.7\,(P_1 - P_0) \tag{4}$$

2.3. Interpretation of results

2.3.1. Constrained modulus - M

The constrained modulus is a parameter related to the soil deformability: the higher the value of M, the higher the stiffness of the soil, so, the less its deformability.

Marchetti [2] and Lunne et al. [3] have already explored a correlation between constrained modulus M and dilatometer modulus E_D in the form of Eq. (5).

$$M = R_M E_D \tag{5}$$

where:

If $I_D \leq 0.6$ → $R_M = 0.14 + 2.36 \log K_D$
If $0.6 < I_D < 3$ → $R_M = R_{M0} + (2.5 - R_{M0}) \log K_D$
$R_{M0} = 0.14 + 0.15\,(I_D - 0.6)$
If $3 \leq I_D < 10$ → $R_M = 0.5 + 2 \log K_D$
If $I_D \geq 10$ → $R_M = 0.32 + 2.18 \log K_D$

In the equations above, if $R_M < 0.85$ → set $R_M = 0.85$.

3. Results

3.1. Initial thoughts

The horizontal stress index (K_D) provides values from 1.8 to 2.3 in case of normally consolidated (NC) soils. In case of over consolidated (OC) soils, the values of K_D are higher and decrease with depth.

Thus, it's possible to identify the transition between the compacted fill (OC soil) and the natural soil (NC) looking at the results of DMT separately.

From there, it was noted in the isolated tests results (without overlap) that the material index (I_D) and the constrained modulus (M) do not suffer much variation along the landfill.

The DMT-308 was taken as example to illustrate the situation above. It reached a total depth of 15 m, being 6.2 m in landfill and 8.8 m in natural soil. Its results are shown in Fig. 5.

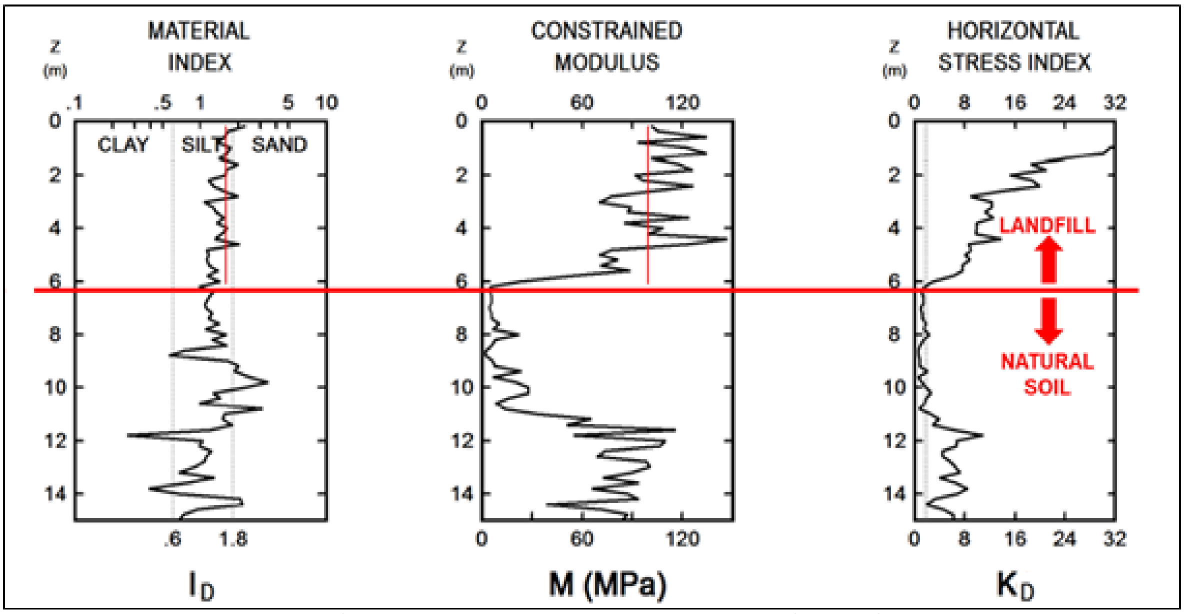

Figure 5. Example of a DMT result (DMT-308), indicating the transition from landfill to natural soil.

The results of material index I_D (mechanical behavior) and constrained modulus M (deformability) presented in the graphs seem to indicate similar characteristics of the soil along the landfill height.

Therefore, it is expected that the values of P_0 (pressure at which the membrane starts to expand) do not present wide variations in landfill, either. This situation can be noted in Fig. 6.

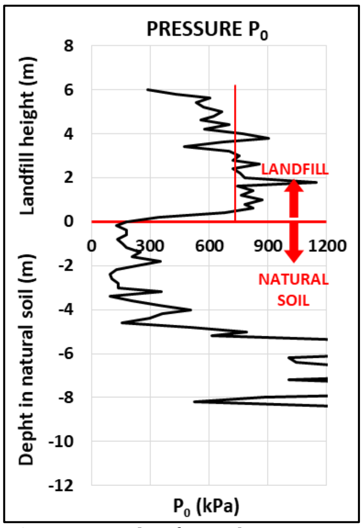

Figure 6. Results of P_0 in the DMT-308.

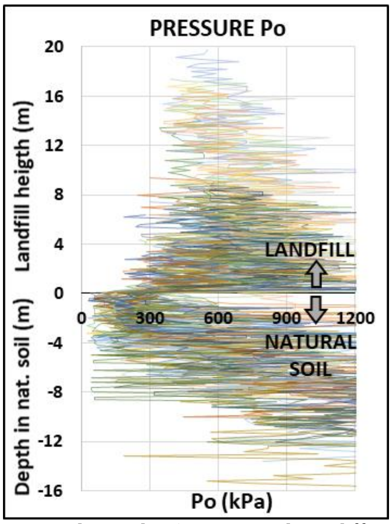

Figure 7. P_0 results overlap (approximately 50 different tests).

3.2. Results overlap

The previous paragraph illustrated that the values of I_D, P_0 and M do not present wide variations along the landfill height for an isolated result of DMT.

Considering that the landfill was executed with the same type of soil and the same compaction control criteria in each point of the construction (theoretically homogeneous), it was expected that the results of I_D, P_0 and M obtained in the compacted fill would be constant (or similar) between each DMT performed.

However, the overlapping results of 50 tests showed that this behavior is not checked.

In relation to the pressure P_0, for example, it can be noted a wide variation of its results even in the landfill, as shown in Fig. 7, in which each color represents a different DMT.

Proceeding with the analysis of the overlapping results, it was observed that the majority of the tests indicated soils with granulometric behavior (I_D) of sand.

Nevertheless, a good part of the tests also indicated soils with granulometric behavior (I_D) of silt.

To verify the difference of P_0 and M variation between the two "types of soil", the results were separated in two groups: Fig. 8 brings the results to "silt" ($0.6 < I_D < 1.8$) and Fig. 9 to "sand" ($I_D > 1.8$).

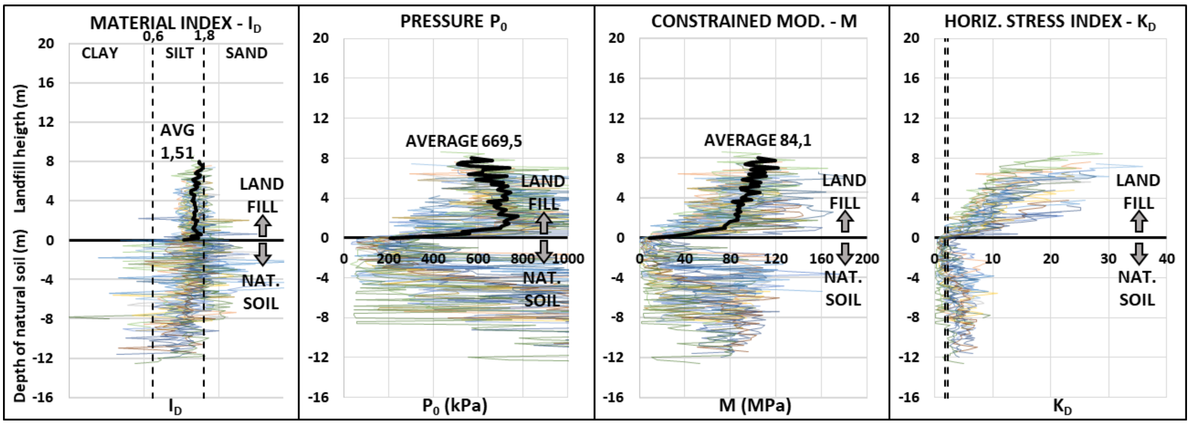

Figure 8. Results of tests that indicated material index of **silt** in landfill.

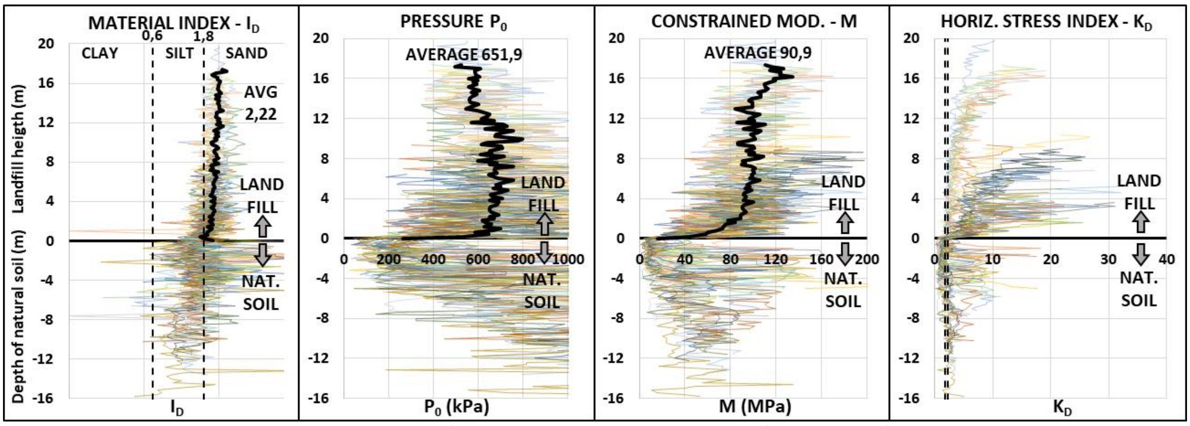

Figure 9. Results of tests that indicated material index of **sand** in landfill.

Somewhat, it was expected that the group with material index of silt had presented lower parameters of resistance when compared to the group with I_D of sand. In other words, it was expected that their values of P_0 and M had appeared more to the left (x-axis) of the graphs.

However, Fig. 8 and Fig. 9 show that P_0 variation (from 300 to 1,000 kPa) and M variation (from 40 to 140 MPa) did not present a great difference between the two groups of distinct granulometric behavior.

The averages calculated to these parameters were indeed very similar between the two groups.

Fig. 10, therefore, illustrates all of the DMT results in an overlap, not separating the group of silt from the group of sand.

An important observation about the graphs of Fig. 10 is that the bottom 1.5 m of the landfill (on top of the natural soil) presented lower values of the parameter M. This indicates that this part of the compacted fill is more susceptible to deformations, due to its contact with the natural soil which, as a general rule, present weaker characteristics of resistance in the first meters depth.

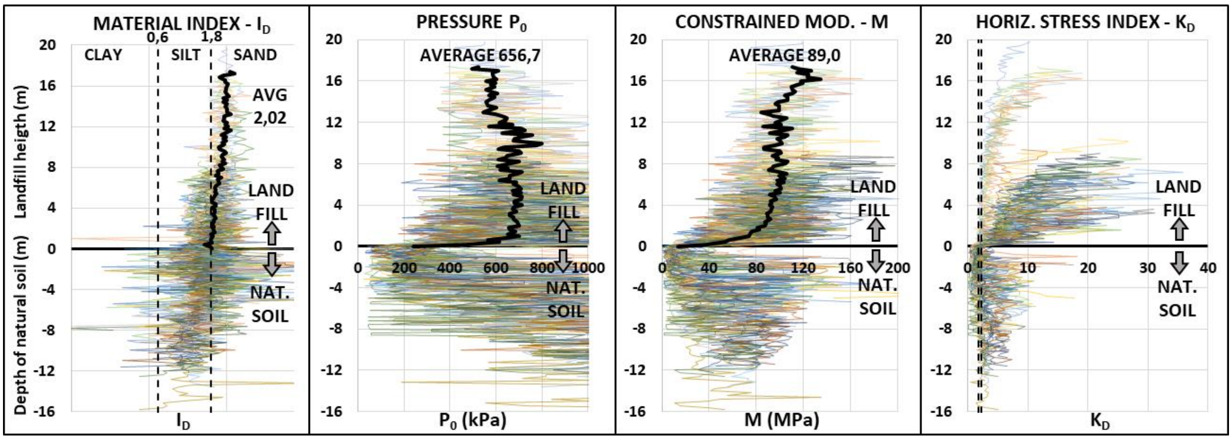

Figure 10. Results overlap of **all** DMT tests.

3.3. Comparison between the rigorously controlled compacted fill and another fill without strict compaction control

The objective here is to compare the variation of P_0 and M in two different constructions located at the same city, in which the same type of soil was used to execute the landfill.

In the first construction site – the one studied previously in this paper - a rigorous control of the compacted fill was required, with degree of compaction 98% of standard Proctor.

In the second one, the landfill was executed without a rigorous compaction control.

The values of P_0 and M obtained in landfill for each case were arranged in normal distribution patterns. The specification limits (upper – USL and lower - LSL) were determined to a confidence level (CL) of 90%.

As previously mentioned, the bottom 1.5 m of landfill presents higher deformability (lower values of P_0 and constrained modulus M), even with a rigorous compaction control. This occurs because this part of the fill is supported on the first layers of natural soil, which do not present good characteristics of resistance.

Thus, the first 1.5 m of landfill height was ignored (in the two cases). It means that its values of P_0 and M are not shown in the related distributions.

Fig. 11 presents the P_0 normal distribution in the rigorously controlled compacted fill.

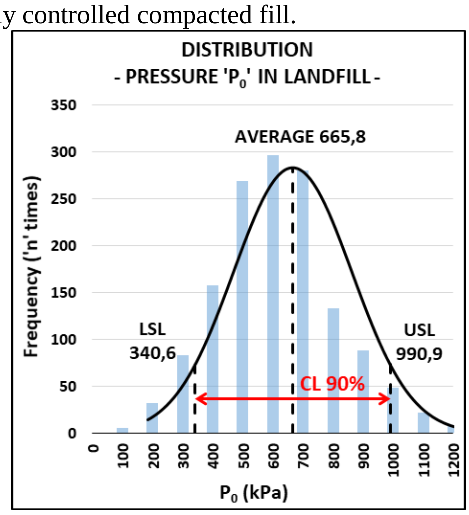

Figure 11. P_0 distribution in the **rigorously controlled** landfill.

Fig. 12 presents the P_0 normal distribution in the landfill executed without a strict compaction control.

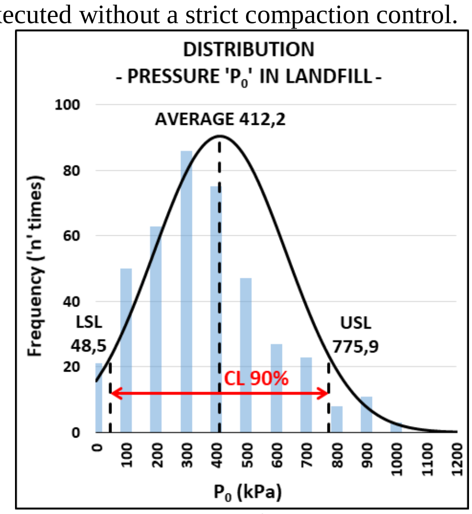

Figure 12. P_0 distribution in the landfill **without compaction control**.

The Fig. 13 presents the overlapping results of P_0 in the rigorously controlled compacted fill.

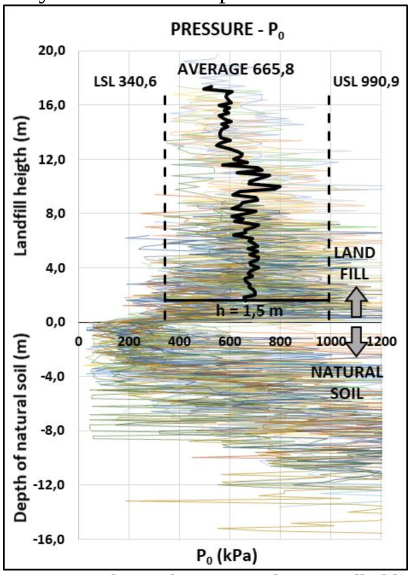

Figure 13. P_0 overlap in the **rigorously controlled** landfill.

Fig. 14 presents the M normal distribution in the rigorously controlled compacted fill.

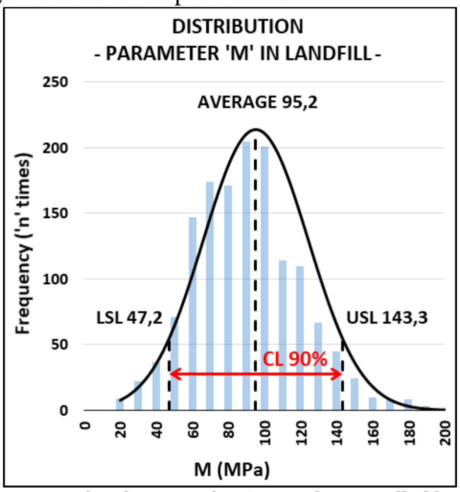

Figure 14. M distribution in the **rigorously controlled** landfill.

Fig. 15 presents the overlapping results of M in the rigorously controlled compacted fill.

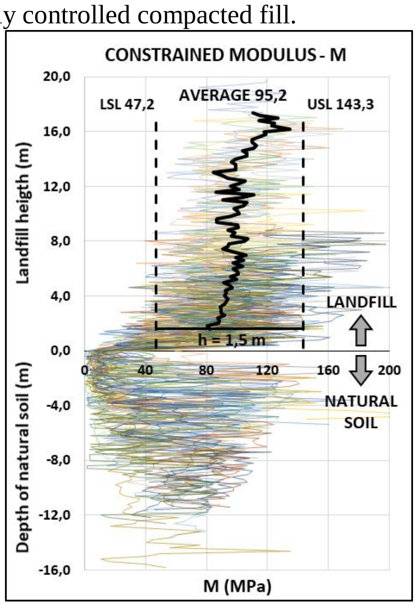

Figure 15. M overlap in the **rigorously controlled** landfill.

Fig. 16 presents the overlapping results of P_0 in the landfill executed without a strict compaction control.

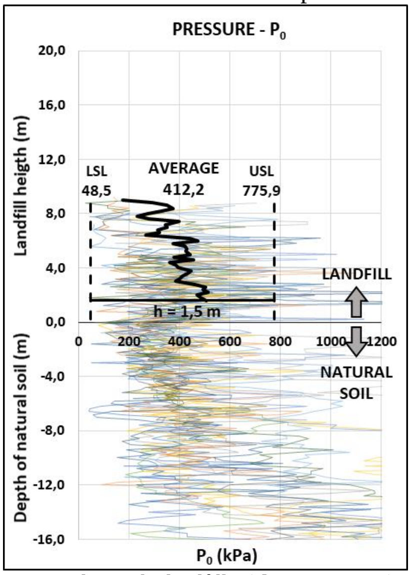

Figure 16. P_0 overlap in the landfill **without compaction control**.

Fig. 17 presents the M normal distribution in the landfill executed without a strict compaction control.

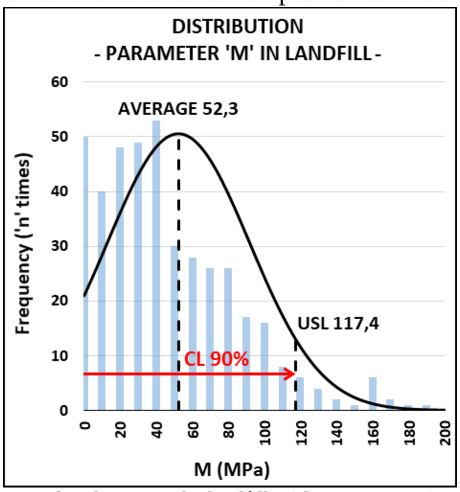

Figure 17. M distribution in the landfill **without compaction control**.

Fig. 18 presents the overlapping results of M in the landfill executed without a strict compaction control.

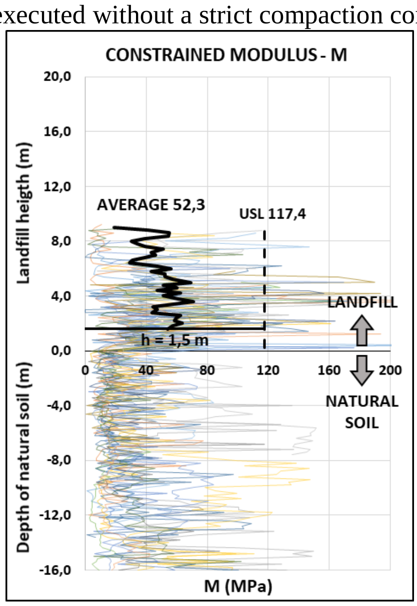

Figure 18. M overlap in the landfill **without compaction control**.

As additional information, Fig. 19 and Fig.20 present some pathologies observed in the second site studied in this work, where the landfill was executed without a strict compaction control.

Figure 19. Fissures observed on the inside concrete floor.

Figure 20. Displacements observed on the external asphalt pavement.

These pathologies are related to some displacements measured by local geotechnical instrumentation, as shown in Fig. 21.

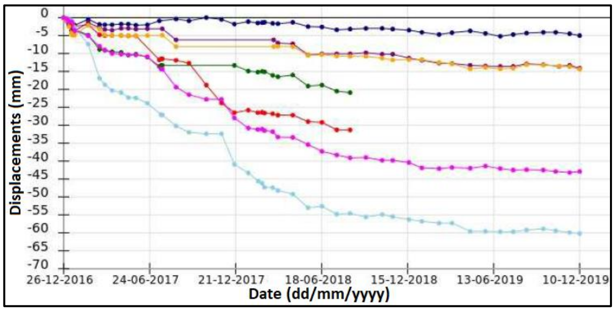

Figure 21. Settlements measured by geotechnical instrumentation.

Over time, it can be noted accumulated settlement values of about 60 mm, developing by the intensity of 3 mm per month. After the reinforcement execution, at the beginning of 2018, the settlements started to establish.

It's important to say that other pathologies were observed before the geotechnical instrumentation, which means that, in fact, the accumulated settlement since the implementation of the industrial shed is possibly higher than the 60 mm measured.

4. Conclusions

The overlapping results showed that the values of I_D, P_0 and M were not constants on all DMT verticals of the construction, although it's a homogeneous landfill (same type of soil and compaction control).

Then, it was possible to conclude that a rigorous compaction control ($\overline{M}$ = 95.2 MPa) can reduce the landfill deformability by the half when compared to other results of DMT performed in a nearby site, at the same city, with the same type of soil in the landfill, but without a strict compaction control ($\overline{M}$ = 52.3 MPa).

It's important to point out that some pathologies were observed in the construction built over the landfill without strict compaction control, such as fissures on the inside concrete floor and on the external asphalt pavement. Therefore, this fact reforces the necessity of rigorous compaction control.

On the other hand, the tests also indicated that the bottom 1.5 m of the landfill are more susceptible to deformations, even in rigorously controlled compacted fill.

So, these results increases the knowledge about the behavior of the landfill bottom portion, which usually does not receive any improvement to limit its displacements, even when the natural soil presents weaker characteristics of resistance.

In this regard, by the experience acquired, it's recommendable that the earthwork (design and construction) predicts a superficial improvement of the natural soil before the landfill execution. This improvement, by the way, would be more effective in the transition between cutting and landfill, where the landfill heights are lower and so the natural soil impacts in the deformability (pressure bulb reaches the natural soil).

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