# APPLICABILITY OF HILF'S METHOD TO THE COMPACTION CONTROL OF SOIL-ROCK MIXTURES

**Andrea Brito, Laura Caldeira[†] and João Maranha[‡]**

[*] Laboratório Nacional de Engenharia Civil (LNEC)
Av. do Brasil, 101, 1700-066 Lisboa, Portugal
e-mail: andreabrito@lnec.pt, webpage: http://www.lnec.pt

**Keywords:** Soil-rock mixtures. Hilf`s Method. Compaction Control. Odelouca Dam

**Abstract**. *The employment of non traditional materials, such as soil-rock mixtures, in the construction of earthworks, for economical and environmental reasons, poses some new challenges to compaction techniques and their control. Usually, this kind of material results from the bulky rock extraction without explosives, and it can include some large size particles (greater than 0.5 m). Construction control of embankments built with soil-rock mixtures is still a subject that needs investigation, considering that it is necessary to extrapolate current test results, which have been reached by means of the truncation of the grain-size distribution curve, to the actual construction conditions. The behaviour of these materials depends of the relative fractions of theirs constituents, becoming closer to a soil, if the fine fraction is large with the coarser material scattered in it, or closer to a rockfill if the coarser particles are in contact with each other with the fines occupying the spaces between them. One of the control methods widely used in Portugal for embankments is the Hilf's method, developed for fine soils, since it does not need a previous knowledge of the materials' characteristics. So, taking into account the materials used in the Odelouca Dam's shells (weathered schist with a significant fraction of large size particles), constructed in the South of Portugal, this paper presents the results from a laboratory study related to the conditions of application and the applicability of Hilf's method to coarser soils and soil-rock mixtures. A series of laboratory tests were performed in a large-scale compactor (Toni-tecnik, with a mould diameter of 300 mm). The obtained results of the upstream shell during the construction of Odelouca Dam are presented, seeking his comparison with the Hilf's method, which avoids the truncation of the material grain-size distribution curve and the subsequent correction of the results. Some conclusions are drawn about the applicability of this method.*

## 1 INTRODUCTION

In the embankment construction, the materials resulting from the compaction must comply with certain requirements included in the design specifications. Depending on the

[†] Laboratório Nacional de Engenharia Civil (LNEC)
Av. do Brasil, 101, 1700-066 Lisboa, Portugal
e-mail: laurac@lnec.pt, webpage: http://www.lnec.pt
[‡] Laboratório Nacional de Engenharia Civil (LNEC)
Av. do Brasil, 101, 1700-066 Lisboa, Portugal
e-mail: jmaranha@lnec.pt, webpage: http://www.lnec.pt

material type, it is opportune to ensure certain values of various parameters, such as unit weight, deformability, permeability and shear strength, in order to verify the assumptions established in the design. Generally, the requirements for road and railway embankments are less restrictive than the requirements for embankment dams and are specified only in terms of deformability and strength.

However, the direct and individualized determination of each of these parameters involves a workload and carrying out times incompatibles with the current construction rhythms, so the option is to make direct or indirect assessment of relevant properties from which to consider the remaining guaranteed.

An indirect way to control the characteristics of an embankment of compacted soil is the determination of dry density and water content. These two parameters thus become gauges of the embankment quality. Nevertheless, the precise determination of water content takes overnight oven drying. Because of that, in 1959, Dr. Jack Hilf (1) proposed a fast method of construction control, which alleviated the need to determine water content.

However, this method was developed for fine soils. So, this paper presents a testing program performed in a soil-rock mixture that allows establishing the applications conditions and the applicability of Hilf's method to this kind of material. The material used in this study comes from the Odelouca Dam shells and it is composed by weathered schist and greywacke with a significant fraction of oversized particles.

## 2 HILF`S METHOD DESCRIPTION

In 1959, Hilf (1) proposed a method of construction control using wet densities only. According to (2), Hilf's method is a compaction control method that allows the determination of the degree of compaction and the optimum water content deviation without the previous knowledge of the corresponding water content, as well as the ignorance of the Proctor reference curve.

This method allows, with certain closeness, to justify the decision of acceptance or rejection of layers within a sufficiently short term, without causing significant disruptions or interruptions to the construction work.

Basically, the proceeding consists in performing an *in situ* sand cone test (ASTM D1556 (3)) for the density determination of the layer in analysis. Then, the material collected in the embankment is taken to the laboratory. The sample is divided in, at least, three specimens. One specimen, with the in work placing humidity, is compacted, in the Proctor mould, with a standard effort and the respective density is determined. In a proper graphic (for this kind of tests, see Figure 1), the obtained density value is plotted in the 0% of water variation vertical line – *point A*.

Next step consists in adding to the second specimen about 2% of weight of water and to perform a new compaction, in aim of the new density determination. The new density value, referred to *in situ* water content (*transformed density*), is plotted in the +2% of water addition vertical line in the graphic (*point B*).

The determination of a third point (*point C*) depends on the relative position of points *A* and *B*. If point *B* has a transformed density higher than point *A*, a 4% of material weight of water is added to the third specimen. A new compaction is performed and the corresponding density is determined. Dividing this value for 1.04, one finds out the dry density referred to the natural water content (*point C*). The correspondent value is plotted in 4% water addition vertical line, in the same graphic.

On the other hand, if point *B* was a transformed density inferior to point *A*, the specimen should be dried (in about 2% of its weight) to perform a new compaction. The three obtained points are sufficient to define a parabolic curve with a vertical axe, corresponding to the transformed density related to the in work placing water content, if the endpoints have ordinates below the midpoint. Otherwise, it’s necessary to perform another compaction, with a different quantity of water, to determine a fourth point.

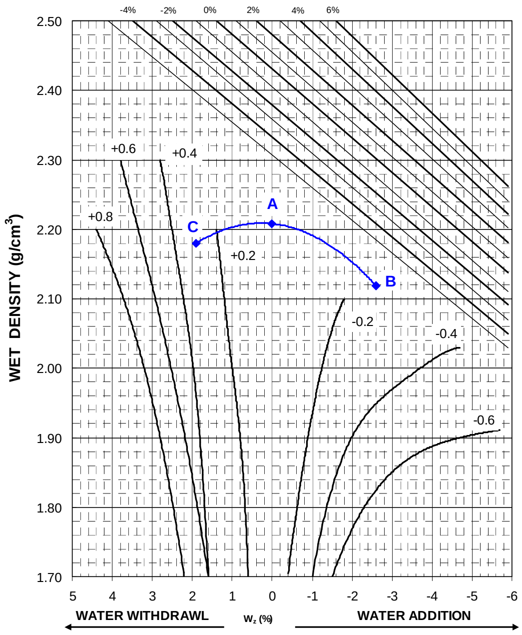



Figure 1: Hilf`s method graphic.

After that, the three points closer to the maximum transform density must be chosen. Through these points a vertical axis parable (named the *transform wet density curve*) should be drawn and its peak coordinates are calculated (point with the maximum density).

The degree of compaction (*D*) is then evaluated by the expression:

$$D = \frac{In\ situ\ density}{Density\ corresponding\ to\ the\ parable\ peak} \tag{1}$$

The compaction efficiency (*C*) can be express by:

$$C = \frac{In\ situ\ density}{Density\ at\ 0\%\ deviation\ of\ water} \tag{2}$$

The difference between the optimum water content and the *in situ* water content $(w_{opt} - w)$ can be related with the abscissa of the parable peak (percentage of water added correspondent to the maximum transformed density). The water content deviation is calculated by adding to the peak abscissa the value indicated in the printed (black) curve closest to the peak. This correction is necessary to convert the percentage of water added or extracted in relation to the *in situ* conditions into the water content deviation.

The *ASTM D5080* (2000) (4) recommends that the soil being tested should be checked with Figure 2 to confirm if the soil values plot within the limits of $\mp 2$ standard deviations. If the data are within these limits (between the red and the green lines), the value of $(w_{opt} - w)$ determined by the Hilf’s method will be within $\mp 0.1$ to 0.2 percentage point of the difference between the in-place moisture content and the optimum moisture content when these two values are determined by oven drying. Special moisture adjustments values must be developed for soils that fall outside the acceptable limits.

A negative value of $(w_{opt} - w)$ indicates that the in-place soil is drier than the optimum moisture point, while a positive value indicates the opposite.

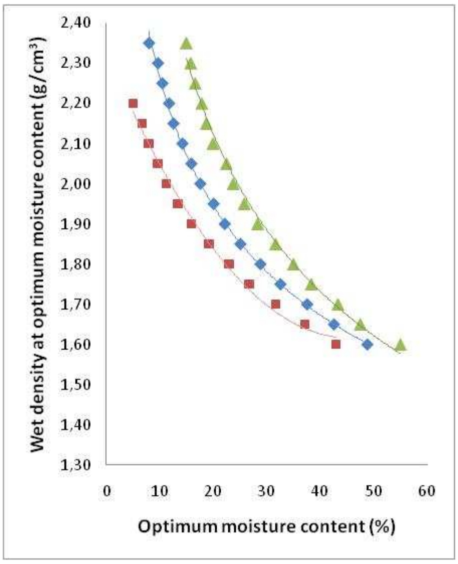



Figure 2: Wet density at the optimum water content versus optimum water content.

As one can realize by the brief description, this method is relatively quick and easy to use, giving results with a high degree of approximation, and is therefore widespread in the compaction control of embankments. Nevertheless, the method only provides relative magnitudes (of compaction degree and water content deviation). So, it is common to complement with the overnight oven determination of the *in situ* water content and the specimens water content after compaction, which allows the assessment of the dry density and establishment of the compaction curve based on three points.

## 3 GENERAL CHARACTERISTICS OF ODELOUCA DAM

Odelouca dam is a zoned embankment dam, with 76 m of height, located in Algarve, in south of Portugal. The crest of dam, with 11 m of width, is about 415 m long (Figure 3a)).

The reservoir created by Odelouca dam as 7.8 $km^2$ surface and 157 $hm^3$ capacity to the maximum water level. Most part of this regularize volume is intended for water supply and a small part will be use to irrigate the downstream field.

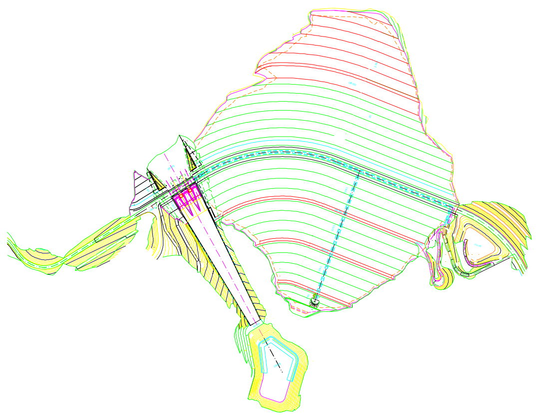
The embankment materials are clayey soil, at the core, and weathered schist and greywacke, with a significant fraction of oversized particles, at the shells (Figure 3b)). The use of materials essentially coming from the reservoir, in the cross-section selected, minimize the environmental negative impacts of the borrow areas exploration. The upstream slope incorporates the cofferdam creating a 14 m wide berm.

Regarding the outside geometry of the earthwork, the upstream slope is inclined 1:2.25 (V:H), beneath the berm, and 1:2 (V:H), above it. The downstream slope is inclined 1:2.25 (V:H), above the crest of the rockfill toe and 1:1.5 (V:H) beneath it.

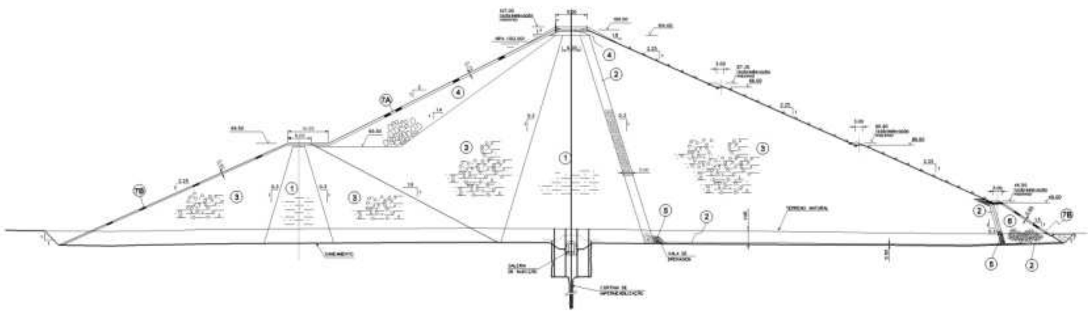
## 4 TESTING PROGRAM

### 4.1 Applications conditions and applicability of Hilf's method to coarser soils

As mentioned above, this method was developed only for fine soils. So, in order to set the applications conditions and the applicability of Hilf's method to coarser soils, a testing program was implemented.



a)



b)

Figure 3: a) Odelouca dam plant. b) Odelouca dam cross-section.

First step consisted in performing Proctor tests to establish the reference compaction curves for the material passing the ¾" sieve, from the *ASTM series*, and for the material passing the #4 sieve. In Figure 4 it's possible to see the grain size distribution curves of the material used in these tests that came from the Odelouca dam shells (weathered schist and greywacke).

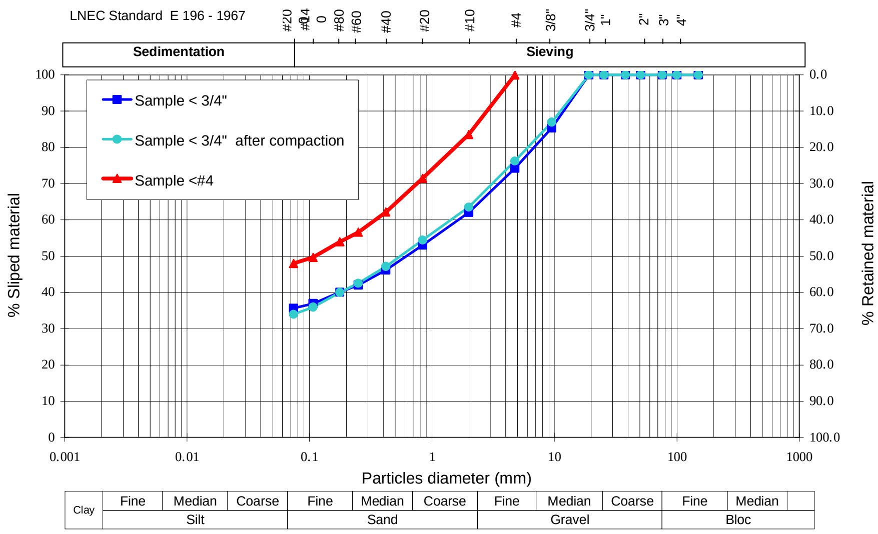
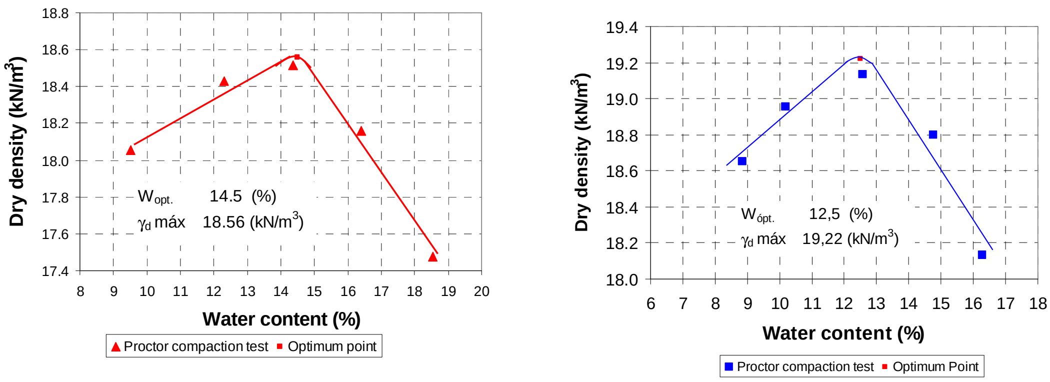



Figure 4: Grain size distribution curves.

As one can realize by regarding the sample with particles with dimensions less than ¾”, before and after compaction, there are no evolution of the grain size distribution with compaction.

Figure 5 shows the reference compaction curves obtained for the two samples analyzed.

The optimum water content is equal to 14.5% and 12.5%, respectively, for the minus # 4 sieve material and for the minus ¾” sieve material, and the maximum dry density is, in that order, equal to 18.56 and 19.22 kN/m$^3$.



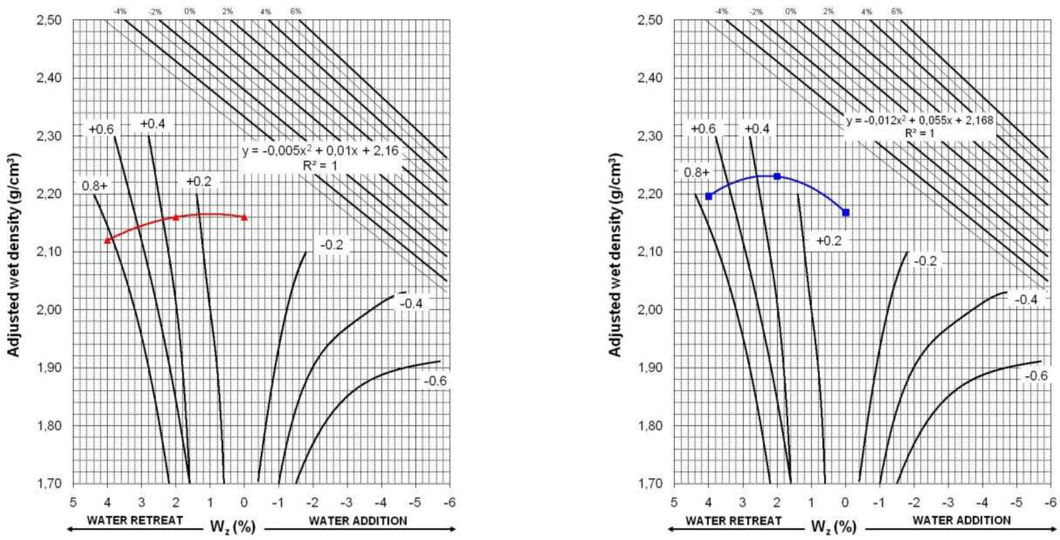

a) b)

Figure 5: Proctor reference compaction curves for: a) the minus #4 sieve material and b) the minus ¾” sieve material.

After the determination of the Proctor reference curve, Hilf’s method was applied, in laboratory, simulating three *in situ* water contents, differing approximately 1% from each other, for the two material gradations. The results are presented in Table 1. As an example, Figure 6 represents the results obtained for the point located in the dry side of the compaction curve, respectively, for the minus # 4 sieve material and for the minus ¾” sieve material.

| Material | Point | $\Delta w$ (%) | $\gamma_{transf}$ (kN/m$^3$) | $\gamma_{transf,p}$ (kN/m$^3$) | $w_{opt} - w$ (%) |
|---|---|---|---|---|---|
| Minus ¾” sieve | Optimum | 0 | 21.88 | 21.70 | 0.60 |
| | | 2 | 21.60 | | |
| | | -2 | 21.00 | | |
| Minus number 4 sieve | | 0 | 21.31 | 21.10 | -0.38 |
| | | 2 | 20.91 | | |
| | | -2 | 21.11 | | |
| Minus ¾” sieve | Dry | 0 | 21.29 | 21.46 | -1.10 |
| | | -2 | 21.39 | | |
| | | -4 | 20.50 | | |
| Minus number 4 sieve | | 0 | 20.91 | 21.12 | -1.57 |
| | | 2 | 21.08 | | |
| | | -2 | 20.41 | | |
| Minus ¾” sieve | Wet | 0 | 21.27 | 21.89 | 2.64 |
| | | 2 | 21.88 | | |
| | | 4 | 21.54 | | |
| Minus number 4 sieve | | 0 | 21.19 | 21.24 | 1.18 |
| | | 2 | 21.19 | | |
| | | 4 | 20.80 | | |

Table 1: Results of the application of Hilf’s method to soils.




a) b)

Figure 6: Application of Hilf's method for a point located in the dry side of the compaction curve: a) the minus # 4 sieve material and b) the minus ¾" sieve material.

Subsequent to the application of the Hilf's method, the material was set overnight in the oven for drying and the water content was found ($w_{oven}$). The comparison between the results obtained with Hilf's method and with the oven drying for the three *in situ* water contents tested is presented in Table 2.

The water content deviation error ($\Delta w_{error}$), express in Table 2, is defined by the expression

$$\Delta w_{error} = \Delta w_{Hilf} - \Delta w_{Proctor} \tag{3}$$

where, $\Delta w_{Hilf}$ is the water content deviation obtained with the Hilf's method appliance and $\Delta w_{Proctor}$ is the water content deviation obtained with the difference between the oven water content and the Proctor water content.

The degree of compaction error ($D_{error}$), also presented in Table 2, can be express by:

$$D_{error} = \frac{\gamma_{trasnf,p}}{(1+w_{oven})\times\gamma_{d\,máx}} \tag{4}$$

where $\gamma_{transf,p}$ is the parable peak obtained in Hilf's method appliance, $w_{oven}$ is the oven water content and $\gamma_{d\,máx}$ is the Proctor dry density.

| Material | Point | Hilf`s method | | | Proctor reference test | | | $\Delta w_{error}$ (%) | $D_{error}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | $\Delta w_{Hilf}$ (%) | $\gamma_{transf,p}$ (kN/m$^3$) | $w_{oven}$ (%) | $\Delta w_{Proctor}$ (%) | $\gamma_{d\,max}$ (kN/m$^3$) | $(1+w_{oven})\gamma_{d\,max}$ (kN/m$^3$) | | |
| Minus ¾" sieve | Optimum | 0.599 | 21.70 | 13.3 | 0.835 | 19.22 | 21.78 | -0.237 | 0.997 |
| | Dry | -1.100 | 21.46 | 11.5 | -0.963 | | 21.43 | -0.137 | 1.001 |
| | Wet | 2.642 | 21.89 | 14.5 | 1.981 | | 22.00 | 0.661 | 0.995 |
| Minus number 4 sieve | Optimum | -0.383 | 21.10 | 14.8 | 0.319 | 18.56 | 21.31 | -0.702 | 0.990 |
| | Dry | -1.569 | 21.12 | 13.7 | -0.838 | | 21.10 | -0.731 | 1.001 |
| | Wet | 1.180 | 21.24 | 15.9 | 1.449 | | 21.51 | -0.269 | 0.987 |

Table 2: Comparison between the results obtained with Hilf's method and with the oven drying.

As one can realize by regarding Table 2, the water content deviation error varied between -0.7 and 0.7 and the degree of compaction error is very close to 1 (the exact value) for all the points and for the two material gradations analyzed.

This first set of tests performed in laboratory allows concluding that:

1. Hilf's method is applicable indifferently for the material passing the ¾" sieve and for the material passing the #4 sieve.
2. Hilf's method is capable of identify correctly the samples on the wet and on the dry side of the compaction curve for all samples tested.
3. The water content deviations obtained are inferior to 0.8%, even when the water content deviation exceeds 2%.
4. The compaction degree is correctly determined by Hilf's method with an error inferior to 0.01.

## 4.2 Application of Hilf's method to soil-rock mixtures

After establishing the conditions for applying the Hilf`s method to coarser soils, next step of the testing program consisted in performing new tests in order to set up the application conditions of Hilf`s method, with large-scale compactors, to soil-rock mixtures.

The use of a large compactor allows the execution of tests with a more representative material, truncated at 2" sieve, precluding, in this way, the application of corrective equations to take into account the presence of the large particles in the mixture.

In the tests performed in *LNEC*, a Toni-tecnik compactor, with a mould of 300 mm in diameter (see Figure 7), was used. This equipment allowed the execution of tests with a particle maximum dimension of 2" ($\emptyset \cong 6D_{máx}$). The tests were performed with several coarser fractions (the minus ¾" (19.1 mm) fraction) present in the mixture.

a)

b)

Figure 7: Test's equipment: a) Toni-tecnik compactor and b) large mould use in the tests (with 300 mm diameter).

Due to the equipment and the samples range, it was necessary to adapt the standard procedures ((5),(6) and (7)). This adaptation has already been made in some Standard Proctor compaction tests performed for a master thesis carried out in *LNEC* (8).

The Hilf`s method was applied on three different coarser fractions – $P_C$[§]=30%, $P_C$=40% and $P_C$=50%, for two *in situ* water contents – one on the dry side of the compaction curve and the other on the wet side of this curve. The results are presented in Table 3. In soil-rock mixtures, the compaction on the wet side is very difficult due to the back flow of the very plastic fine fraction, so, instead of 2% variation of water between de samples, a variation of 1.5% was adopted.

The material was set overnight in the oven for drying and the water content was found ($w_{oven}$). The comparison between the results obtained with Hilf's method and with the oven drying for the two *in situ* water contents tested is presented in Table 4, as well as the

[§] $P_C$ – it`s the coarser fraction present in the soil-rock mixture correspondent water content deviation error ($\Delta w_{error}$) and degree of compaction error ($D_{error}$).

| Material | Point | $\Delta w$ (%) | $\gamma_{transf}$ (kN/m$^3$) | $\gamma_{transf,p}$ (kN/m$^3$) | $w_{opt} - w$ (%) |
|---|---|---|---|---|---|
| $P_C$=30% | Dry | -1.5 | 21.39 | 21.78 | -2.97 |
| | | -3 | 21.77 | | |
| | | -4.5 | 21.07 | | |
| $P_C$=40% | | 0 | 21.43 | 21.98 | -1.95 |
| | | -1.5 | 21.98 | | |
| | | -3 | 21.81 | | |
| $P_C$=50% | | 0 | 21.21 | 22.08 | -1.82 |
| | | -1.5 | 22.06 | | |
| | | -3 | 21.70 | | |
| $P_C$=30% | Wet | 0 | 22.14 | 22.61 | 1.71 |
| | | 1.5 | 22.60 | | |
| | | 3 | 22.24 | | |
| $P_C$=40% | | 0 | 21.59 | 22.81 | 1.64 |
| | | 1.5 | 22.68 | | |
| | | 3 | 21.59 | | |
| $P_C$=50% | | 0 | 22.35 | 22.56 | 1.05 |
| | | 1.5 | 22.49 | | |
| | | 3 | 21.65 | | |

Table 3: Results of the application of Hilf's method to soil-rock mixtures.

| Material | Point | Hilf`s method | | | Proctor reference test | | | $\Delta w_{error}$ (%) | $D_{error}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | $\Delta w_{Hilf}$ (%) | $\gamma_{adj,p}$ (kN/m$^3$) | $w_{oven}$ (%) | $\Delta w_{Proctor}$ (%) | $\gamma_{d\,max}$ (kN/m$^3$) | $(1+w_{oven})\gamma_{d\,max}$ (kN/m$^3$) | | |
| $P_C$=30% | Dry | -2.97 | 21.78 | 6.99 | -3.26 | 20.1 | 21.51 | 0.29 | 1.013 |
| | Wet | 1.70 | 22.61 | 12.03 | 1.78 | | 22.52 | -0.08 | 1.004 |
| $P_C$=40% | Dry | -1.95 | 21.98 | 8.25 | -1.25 | 20.5 | 22.21 | -0.70 | 0.990 |
| | Wet | 1.64 | 22.81 | 11.08 | 1.58 | | 22.77 | 0.06 | 1.002 |
| $P_C$=50% | Dry | -1.82 | 22.08 | 8.37 | -1.63 | 20.6 | 22.27 | -0.19 | 0.991 |
| | Wet | 1.05 | 22.56 | 11.00 | 1.00 | | 22.81 | 0.05 | 0.989 |

Table 4: Comparison between the results obtained with Hilf's method and with the oven drying for soil-rock mixture for the three coarser fractions tested.

For the different coarser fractions tested, the water content deviation error varied between -0.7 and 0.3 and the degree of compaction error is very close to 1 (the exact value).

This set of tests allows concluding that Hilf's method is applicable to soil-rock mixtures, identifying correctly the samples on the wet and on the dry side of the compaction curve for all samples tested. The water content deviations obtained are inferior to 0.7%, even when the water content deviation exceeds 3%, and the compaction degree is correctly determined by Hilf's method with an error inferior to 0.02.

## 5 ODELOUCA DAM COMPACTION CONTROL

For the shells quality compaction control of the Odelouca Dam, composed by weathered schist and greywacke with a significant fraction of oversized particles, an approach proposed by Torrey and Donaghe in 1994 (9) has been used. So, in 2004, a testing program was implemented in *LNEC* and a set of vibratory and standard compaction tests in large moulds were made in order to obtain some corrective equations to have into account the presence of the large particles in the mixture[**]. The material used in the tests performed in 2004 came from the borrow areas used in the construction of the cofferdam.

During the construction of the main dam, between 2008 and 2009, the material characteristics had slightly changed and the derived equations in 2004 seemed not reflect the current conditions of the embankment. Therefore, additional material was collected from the borrow areas and further tests were carried out. Bearing in mind the use of vibratory rollers at the site, to better reproduce the construction conditions, vibratory compaction tests were used. So, in 2008, some vibratory compaction tests were repeated and new corrective equations were determined.

In the shells compaction control, the original Hilf`s method (applied to the material passing the #4 sieve) was used together with the sand-cone method with the larger apparatus and with the determination of coarser fraction (particles retained in #4 sieve). So, corrective equations were needed in order to have into account the presence of the large particles. Based on the Hilf's results in terms of converted value of the parable peak ($w_{opt}^F, \gamma_{d\,\max}^F$), the optimum water content and the maximum dry density of the integral material were obtained ($w_{opt}^T, \gamma_{d\,\max}^T$) through the application of those corrective formulas.

In 1994, Torrey and Donaghe defined two additional quantities: the density interference coefficient, $I_C$, and the optimum water content factor, $F_{opt}$ , expressed as:

$$I_c = \frac{100F_F}{P_C G_M} \quad (5)$$

$$F_{opt} = \frac{100w_{opt}^F}{P_C w_{opt}^T} \quad (6)$$

where $F_F$ is the fraction density factor, given by $F_F = \gamma_d^F / \gamma_{d\,max}^F$ , $\gamma_d^F$ the dry unit weight of the finer fraction and $G_M$ the soil particles density of the coarser fraction.

To calculate $F_F$, the authors appealed to the following equation:

$$F_F = \frac{\gamma_{d\,max}^T G_M \gamma_w P_F}{100\gamma_{d\,max}^F G_M \gamma_w - \gamma_{d\,max}^T \gamma_{d\,max}^F P_C} \quad (7)$$

Table 5 presents the original and deduced equations in 2004 and 2008. This corrective equations were used to compared the results obtain in the construction control.

| Test | $I_C$ | $F_{opt}$ |
|---|---|---|
| Torrey and Donaghe (1994) | $\log I_C = 1.614 - 1.025 \log P_C$ <br> $R^2 = 0.99$ | $\log F_{opt} = 1.812 - 0.730 \log P_C$ <br> $R^2 = 0.98$ |
| Vibratory Compactions Tests (2004) | $\log I_C = 1.7398 - 1.0935 \log P_C$ <br> $R^2 = 0.9912$ | $\log F_{opt} = 1.8343 - 0.828 \log P_C$ <br> $R^2 = 0.9685$ |
| Vibratory Compactions Tests (2008) | $\log I_C = 1.7371 - 1.0693 \log P_C$ <br> $R^2 = 0.9996$ | $\log F_{opt} = 2.3848 - 1.5805 \log P_C$ <br> $R^2 = 1$ |

$I_C$ – is the interference coefficient;
$F_{opt}$ – is the corrective factor of the optimum water content;
$P_C$ – is the percentage of the coarser material presented in the mixture.

Table 5: Original and deduced corrective equations.

Figure 8 presents the grading size distribution curves of some of the samples collected in the upstream shell. In the analysed tests, the plus #4 sieve (4.75 mm) fraction material ($P_C$) ranged between about 17 and 68%, with the average value of 49%.

Figure 9 and Table 6 contain the results achieved with the application of the corrective equations to the values obtained with Hilf`s method and its comparison with the field in the upstream shell of Odelouca dam compaction control, in terms of water content deviation and compaction degree.

[**] More information about the conditions of the tests performed can be found in (9).

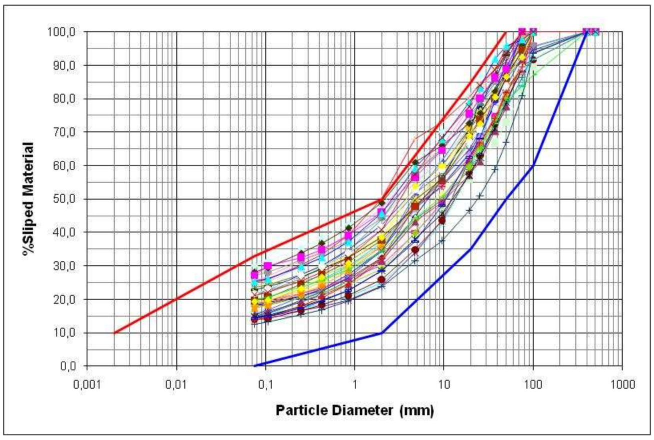
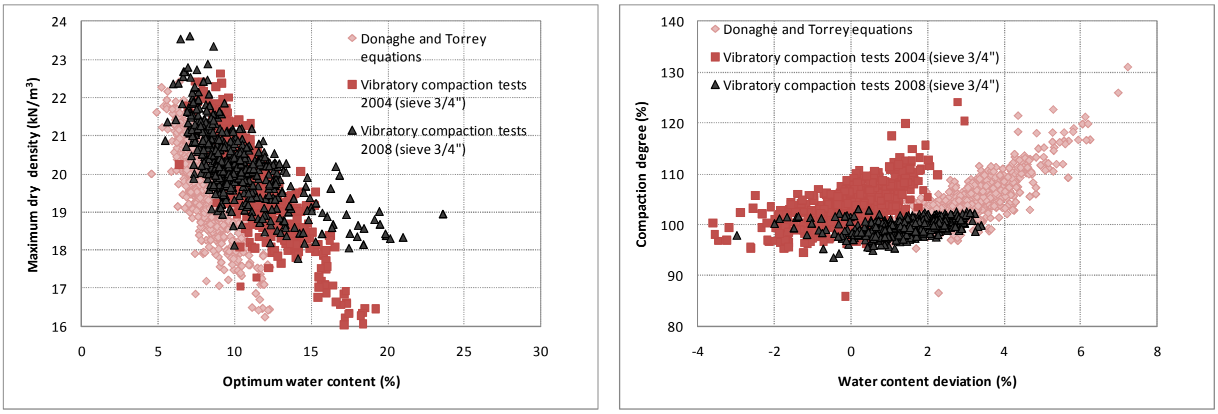



Figure 8: Grading size distribution curves from the Odelouca dam upstream shell




a) b)

Figure 9: a) Maximum dry density *vs* optimum water content and b) compaction degree *vs* water content deviation by the application of Hilf`s method to the fine fraction in the upstream shell of Odelouca dam compaction control.

The obtained results show the strong dependence of the corrective expressions used. This equations in turn depends on the excavated material characteristics, which are very influenced by the borrow area and the excavation depth, being more fractured and weathered at the surface and of better quality in deep.

So, according to the Donaghe and Torrey equations, the upstream shell was compacted in the wet side, with a minimum water content of 0.6% and a maximum of 7.2%, with an average of 3.2%. However, if one considers the equations obtained in the vibration tests, the embankment was compacted to values closer to the optimum point, for the vibratory tests performed in 2004, and about 1.5% in relation to the optimum water content, on the wet side, based on the tests performed in 2008, in terms of the average values. On other hand, the variance was minimized considering the most recent laboratory tests.

The observation of the compacted material in the field denoted that the material was being compacted on the wet side, but near the optimum content. Therefore, the equations that best reproduce the data observed *in situ* are those obtained in the tests performed in 2008.

Regarding the results obtained with the tests performed in 2004 and in 2008, one can conclude that the use of corrective formulas in soil-rock mixtures, to take into account the oversized particles, demands the execution of laboratory compaction tests all along the construction and the deduction of the correspondent equations, in order to reflect the differences between the materials collected in the borrow areas over time. Alternatively, this paper shows that the Hilf's method can be applied directly if a large compactor is available.

| | Test | $\gamma^T_{d\,máx}$ (kN/m$^3$) | $w^T_{opt}$ (%) | $\Delta w$ (%) | $GC$ (%) |
|---|---|---|---|---|---|
| Maximum | Donaghe and Torrey (1994) | 24.8 | 15.3 | 7.2 | 131.0 |
| Minimum | | 14.0 | 4.6 | 0.6 | 86.5 |
| Average | | 19.2 | 8.3 | 3.2 | 105.0 |
| Stand. deviation | | 1.3 | 1.7 | 1.1 | 4.8 |
| Variance | | 1.8 | 2.8 | 1.2 | 23.3 |
| Maximum | Vibratory compactions tests (2004) | 25.0 | 19.2 | 3.0 | 124.1 |
| Minimum | | 14.8 | 6.4 | -3.0 | 85.8 |
| Average | | 19.5 | 11.6 | 0.0 | 103.4 |
| Stand. deviation | | 1.2 | 2.1 | 1.0 | 4.0 |
| Variance | | 1.5 | 4.5 | 1.0 | 16.1 |
| Maximum | Vibratory compactions tests (2008) | 23.6 | 23.6 | 3.4 | 103.1 |
| Minimum | | 17.8 | 5.4 | -3.0 | 93.4 |
| Average | | 20.3 | 10.1 | 1.5 | 99.5 |
| Stand. deviation | | 0.9 | 2.5 | 0.9 | 1.5 |
| Variance | | 0.9 | 6.5 | 0.8 | 2.3 |

Table 6: Representative values of the quality control applied to Odelouca upstream shell, according to the different corrective equations.

## 6 CONCLUSIONS

This paper presents the results from an investigation laboratory study relatively to the applications conditions and the applicability of Hilf's method to coarser soils and soil-rock mixtures.

Construction control of embankments built with soil-rock mixtures is still a subject that needs investigation, considering the need to extrapolate current test results, which have been reached by means of the truncation of the grain-size distribution curve, to the actual construction conditions.

One of the control methods widely used in Portugal for embankments is the Hilf's method, developed for fine soils, since it does not need a previous knowledge of the materials' characteristics. So, using the materials of Odelouca Dam's shells (weathered schist with a significant fraction of large size particles), the results from an laboratory study related to the conditions of application and the applicability of Hilf's method to coarser soils and soil-rock mixtures were presented.

Series of laboratory tests were performed with traditional and large-scale compactors (Toni-tecnik, with a mould diameter of 300 mm) and different percentages of coarser fraction. The use of this large-scale compactor avoids the truncation of the material grain-size distribution curve and the subsequent correction of the results.

Some conclusions are drawn about the applicability of this method:

1. Hilf's method is applicable indifferently for the material passing #4, ¾" and 2" sieves.
2. Hilf's method is capable of identify correctly the samples on the wet and on the dry side of the compaction curve for all samples tested.
3. The water content deviations obtained are inferior to 0.9%, even when the water content deviation goes beyond 2%.
4. The compaction degree is correctly determined by Hilf's method with an error inferior to 0.01.

The compaction control of Odelouca shell materials involved the application of Hilf's methods to the fraction passing the #4 sieve, for the evaluation of the maximum dry density and optimum water content of the finer fraction. For taking into account the oversized particles, corrective formulas were applied to these results, in order to calculate the maximum dry density and the optimum water content of the soil-rock mixture.

Based on the work of Torrey and Donaghe (9), some laboratory tests were executed, in 2004, during the execution of the cofferdam, and in 2008, during the execution of the main dam, for the calibration of those corrective formulas. These expressions, together with the original expression, were applied to the compaction results of upstream shell. These results were compared with those from the construction of Odelouca Dam.

Regarding the results obtained, one can conclude that the use of corrective formulas in soil-rock mixtures, to take into account the oversized particles, demands the execution of laboratory compaction tests all along the construction and the deduction of the correspondent equations, in order to reflect the differences between the materials collected in the borrow areas over time.

Alternatively, this paper shows that the Hilf's method can be applied directly if a large compactor (like Toni-tecnik with mould diameter = 300 mm) is available, with no truncation of the material gradation curve, rendering the quality control more accurate and easily to do.

## ACKNOWLEDGMENTS

The authors would like to thank the contribution from the work Owner - the Águas do Algarve, SA, for the present work, in particular, the availability of materials to the tests. We would like to express gratitude to the LNEC technicians, especially to Mr. António Cardoso and Mr. Joaquim Timóteo for the development of experimental work.

## REFERENCES

1. **Hilf, Jack.** A Rapid Method of Construction Control for Embankments of Cohesive Soil. *Engineering Monograph No.26, Bureau of Reclamation.* 1959, p. 23.

2. **Guedes de Melo, F.** Compactação de aterros de barragens de terra. *Laboratório Nacional de Engenharia Civil, ICT, Geotecnia, S330.* 1985.

3. **American National Standard - ASTM - D1556.** Standard test method for density and unit weight of soil in place by the sand-cone method. 2000.

4. **American National Standard - ASTM - D5080.** Standard test method for rapid determination of percent compaction. 2000.

5. **E 197-1966.** Solos. Ensaio de compactação. *LNEC.* 1966.

6. **American National Standard - ASTM - D698-00a.** *Standard test methods for laboratory compaction characteristics of soil using standard effort (12.400 ft-lbf/ft3 (600 kN-3/m3)).* 2000.

7. **USBR 5515-89.** *Procedure for performing laboratory compaction of soils containing gravel.* Denver, Colorado : U.S. Dept. of the Interior. Bureau of Reclamation, 1989.

8. **Brito, Andrea.** *Compactação de aterros de barragens. Novas metodologias de controlo.* Lisbon : Dissertação de Mestrado. Instituto Superior Técnico. Univerdidade Técnica de Lisboa, 2006.

9. **Torrey, V. H. and Donaghe, R. T.** Compactions control of earth-rock mixtures: a new approach. 1994, Vol. 17, 3.