Applicability of Hilf's method to the compaction control of soil-rock mixtures

Andrea Brito*, Laura Caldeira* and João Maranha*

ABSTRACT

The employment of non-traditional materials, such as soil-rock mixtures, in the construction of earthworks, for both economical and environmental reasons, poses new challenges to compaction techniques and their control. Usually this kind of material results from bulky rock extraction without explosives, and can include some large particles (>0.5m). Construction control of embankments built with soil-rock mixtures is still a subject that needs investigating, 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 on the relative fractions of their constituents, becoming closer to soil if the fine fraction is large with the coarser material scattered in it, or closer to rockfill if the coarser particles are in contact with each other with the fines occupying the spaces between them. One of the techniques widely used in Portugal for the control of embankments is the Hilf method, developed for fine soils since it does not need previous knowledge of the material's characteristics. Therefore, taking into account as an example the materials used in Portugal's Odelouca Dam's shells (weathered schist with a significant fraction of large-size particles), 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, and the results obtained from the upstream shells during the construction of the Odelouca Dam are presented, with the aim of seeking the authors comparison with Hilf's method, which avoids truncation of the material grain size distribution curve, and the subsequent correction of the results. Some conclusions are then drawn about the applicability of this method.

Keywords: Soil-rock mixtures, Hilf's method, compaction control, Odelouca Dam.

1. INTRODUCTION

During embankment dam construction the materials resulting from compaction must comply with certain requirements included within the design specifications. Depending on the material

**Laboratório Nacional de Engenharia Civil (LNEC), Av. do Brasil, 101, 1700-066 Lisbon, Portugal; Email: andreabrito@lnec.pt, laurac@lnec.pt, jmaranha@lnec.pt, Webpage: http://www.lnec.pt*

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. However, direct and individualized determination of each of these parameters involves a heavy workload and execution times incompatible with current construction rhythms, so the only option is to make either a direct or indirect assessment of the relevant properties from which to consider the remaining parameters.

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's quality. Nevertheless, precise determination of the soil's water content takes overnight oven drying. Because of this, in 1959 Dr Jack Hilf[1] proposed a faster method of construction control, which alleviated the need to determine the water content. This method, however, was only developed for fine soils. Therefore this paper presents a testing program performed on a soil-rock mixture which allows the application conditions, and the applicability of Hilf's method to this kind of material, to be established. The material used in this study comes from the Odelouca Dam's shells, and is composed of 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 Guedes de Melo[2], Hilf's method is a compaction control technique which allows the degree of compaction, and the optimum water content deviation, to be determined without previous knowledge of the corresponding water content, as well as the ignorance of the Proctor reference curve. This method allows, with a certain amount of accuracy, justification of the decision to either accept or reject certain layers of the embankment within a sufficiently short amount of time, without causing significant disruption to construction work.

Fundamentally, the procedure consists of performing an *in situ* sand cone test[3] to determine the density of the embankment layer being analysed. The material collected is then taken to the laboratory and divided into at least three specimens. One specimen, complete with in-place humidity, is compacted in the Proctor mould and the respective density is determined. The value obtained from this test is then plotted in a graph at the 0% of water variation point on the vertical line - Point A (see Figure 1).

The next step involves adding approximately 2% of weight of water to the second specimen, and then performing a new compaction, with the aim of determining the new density. The new density value, referred to as *in situ* water content (transformed density), is plotted in the +2% of water addition vertical line on the same graph (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, 4% of material weight of water is added to the third specimen. A new compaction is then performed and the corresponding density is determined. Dividing this value by 1.04, it can be determined that the dry density refers to the natural water content (Point C). The corresponding value is then plotted on the 4% water addition vertical line on the graph.

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 axis, corresponding to the transformed density relating to the in-place water content if the endpoints have ordinates below the midpoint. Otherwise it is necessary to perform another compaction, with a different quantity of water, in order to determine a fourth point.

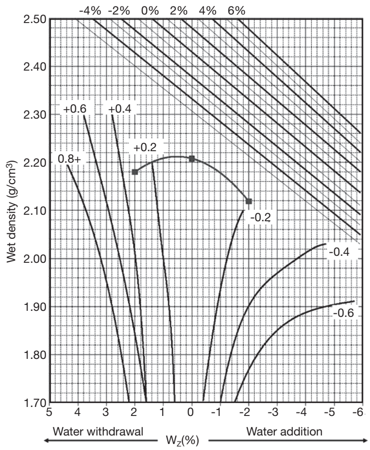


Figure 1. Hilf`s method graphic

After the various compactions have been completed, the three points closest to the maximum transform density must be chosen. Through these points a vertical axis parable, i.e. the transform wet density curve, should be drawn and its peak coordinates calculated to determine the point with the maximum density. The degree of compaction (*D*) is then evaluated using the expression:

$$D = \frac{\textit{In situ} \text{ density}}{\text{Density corresponding to the parable peak}} \qquad (1)$$

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

$$C = \frac{\textit{In situ} \text{ density}}{\text{Density at 0\% deviation of water}} \quad (2)$$

The difference between the optimum water content and the *in situ* water content (w_{opt} - w) can be determined by the abscissa of the parable peak (percentage of water added corresponding to the maximum transformed density). The water content deviation is calculated by adding to the peak abscissa the value indicated in the printed 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[4] recommends that the soil being tested should be checked against Figure 2 to confirm whether or not its values are contained within the limits of ±2 standard deviations. If the data is within these limits then the value of (w_{opt} - w), determined by Hilf's method, will be within the ±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 adjustment 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.

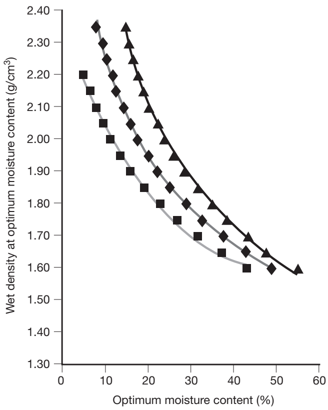
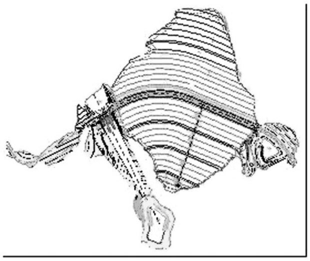


Figure 2. Wet density at the optimum water content *vs* optimum water content

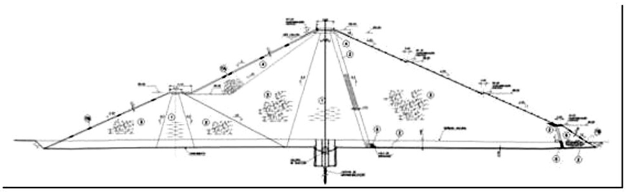
As can be realized from the brief description, this method is relatively quick and easy to use, providing results with a high degree of approximation, and is therefore widely used in the compaction control of embankment dams. Nevertheless, the method only provides relative magnitudes (of compaction degree and water content deviation), so it is common to complement these with the overnight oven determination of the *in situ* water content, and the specimen's water content after compaction, which allows assessment of the dry density and establishment of the compaction curve based on three points.

3. GENERAL CHARACTERISTICS OF ODELOUCA DAM

The Odelouca Dam is a zoned embankment dam, with a height of 76m, and is located in the Algarve, in southern Portugal. The crest of the dam is 11m wide and is approximately 415m in length (see Figure 3a)).



(a)



(b)

Figure 3. a) Odelouca Dam plant; b) Odelouca Dam cross-section

The reservoir created by the Odelouca Dam has a surface area of 7.8km^2, a capacity of 157hm^3 at maximum water level, and is mainly used for water supply and to irrigate the downstream fields.

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

With regard to 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 previously mentioned, Hilf's method was developed only for fine soils. Therefore, in order to set the application's conditions and the applicability of this method to coarser soils, a testing program was implemented.

The first step towards this consisted of performing Proctor tests to establish the reference compaction curves for the material passing through a 3/4"sieve, from the ASTM series, and for the material passing through a #4 sieve. Figure 4 shows the grain size distribution curves of the material used in these tests which, as previously mentioned, came from the Odelouca Dam shells (weathered schist and greywacke). As can be realized by regarding the sample with particle dimensions less than 3/4", before and after compaction, there is no evolution of the grain size distribution after compaction.

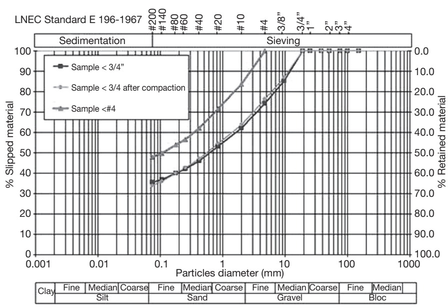
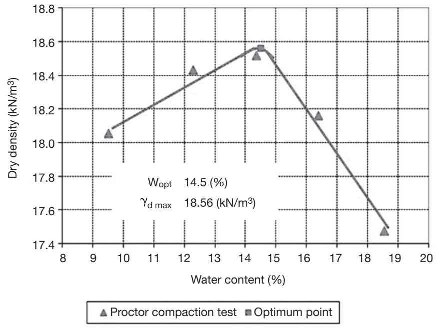
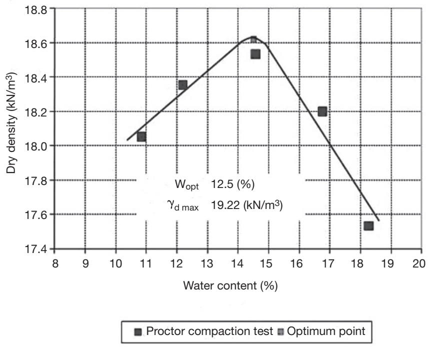


Figure 4. Grain size distribution curves

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



(a)

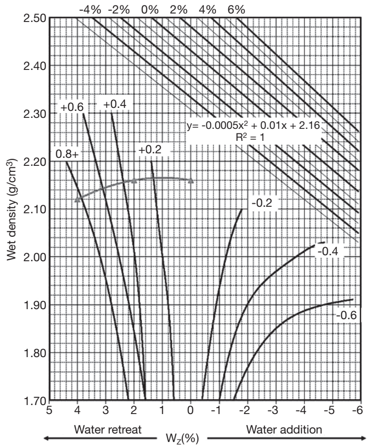


(b)

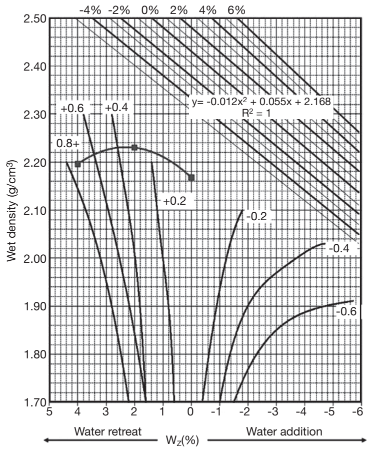
Figure 5. Proctor reference compaction curves for: a) the minus #4 sieve material, and b) the minus 3/4" sieve material

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

After determining the Proctor reference curve Hilf's method was applied in the laboratory, simulating three *in situ* water contents differing approximately 1% from each other for the two material gradations, and the results are presented in Table 1. As an example, Figure 6 represents the results obtained for the point located on the dry side of the compaction curve for the minus #4 and minus 3/4" sieve material, respectively.



(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 3/4" sieve material

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

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

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

The water content deviation error (Δw_{error}) expressed in Table 2 is defined by the expression:

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

where Δw_{Hilf} is the water content deviation obtained with the application of the Hilf method, 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}) is also presented in Table 2, and can be expressed by:

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

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

Material	Point	Hilf`s method			Proctor reference test			Δw_{error} (%)	D_{error}
		Δw_{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 3/4" sieve	Optimum	0.599	21.70	13.3	0.835		21.78	-0.237	0.997
	Dry	-1.100	21.46	11.5	-0.963	19.22	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		21.31	-0.702	0.990
	Dry	-1.569	21.12	13.7	-0.838	18.56	21.10	-0.731	1.001
	Wet	1.180	21.24	15.9	1.449		21.51	-0.269	0.987

Table 2. Comparison of the results obtained using Hilf's method and oven drying

As can be revealed by referring to 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 also for the two material gradations analyzed.

This first set of tests performed in the laboratory leads to the conclusion that:

1. Hilf's method is applicable indifferently for the material passing through a 3/4" and a #4 sieve.
2. Hilf's method is capable of correctly identifying the samples on both the wet and dry side of the compaction curve for all those 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 Hilf's method to coarser soils, the next step in the testing program is to perform new tests in order to set up the application conditions of Hilf`s method to soil-rock mixtures using large-scale compactors.

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

In tests performed at the Laboratório Nacional de Engenharia Civil (LNEC) in Portugal, a Toni-tecnik compactor with a mould diameter of 300mm was used (see Figure 7). This equipment allowed the execution of tests with a particle maximum dimension of 2" ($\varnothing \cong 6D_{max}$). The tests were performed with several coarser fractions (the minus 3/4" (19.1mm) fraction) present in the mixture.

(a) (b)

Figure 7. Test equipment: a) Toni-tecnik compactor, and b) large mould (300mm diameter)

Due to the equipment and sample ranges it was necessary to adapt the standard procedures[5,6,7]. This adaptation has already been made in some standard Proctor compaction tests performed for a master thesis carried out at LNEC[8].

Hilf's method was applied to three different coarser fractions - $P_C^{\S}$ = 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, and 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 a 2% variation of water between the samples, a variation of 1.5% was adopted.

The material was set overnight in the oven for drying and the water content was established (w_{oven}). A comparison of the results obtained using Hilf's method and the oven drying method for the two *in situ* water contents is presented in Table 4, as well as the correspondent water content deviation error (w_{error}), and degree of compaction error (D_{error}).

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 concludes that Hilf's method is applicable to soil-rock mixtures, identifying correctly the samples on both the wet and dry side of the compaction curve for all those 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.

Note: $P_C^{\S}$ = the coarser fraction present in the soil-rock mixture.

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

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

Material	Point	Hilf´s method			Proctor reference test			Δw_{error} (%)	D_{error}
		Δw_{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)		
P_C = 30%	Dry Wet	-2.97 1.70	21.78 22.61	6.99 12.03	-3.26 1.78	20.1	21.51 22.52	0.29 -0.08	1.013 1.004
P_C = 40%	Dry Wet	-1.95 1.64	21.98 22.81	8.25 11.08	-1.25 1.58	20.5	22.21 22.77	-0.70 0.06	0.990 1.002
P_C = 50%	Dry Wet	-1.82 1.05	22.08 22.56	8.37 11.00	-1.63 1.00	20.6	22.27 22.81	-0.19 0.05	0.991 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

5. ODELOUCA DAM COMPACTION CONTROL

For the shells quality compaction control at the Odelouca Dam, an approach proposed by Torrey & Donaghe[9] has been adopted. In 2004 a testing program was implemented at the

LNEC, and a set of vibratory and standard compaction tests in large moulds were conducted in order to obtain some corrective equations which took into account the presence of large particles in the mixture. The material used in these tests came from the borrow areas used in the construction of the cofferdam.

During construction of the main dam, between 2008 and 2009, the material characteristics changed slightly and the equations derived in 2004 did not reflect the current conditions of the embankment. Therefore additional material was collected from the borrow areas and bearing in mind the use of vibratory rollers at the site, to better reproduce the construction conditions, vibratory compaction tests were conducted and a new set of adjusted equations were determined.

In the shells compaction control the original Hilf's method applied to the material passing through the #4 sieve was used, together with the sand-cone method with the larger apparatus, and with the determination of coarser fractions (particles retained in the #4 sieve). Therefore corrective equations were also needed in order to take into account the presence of these larger particles. Based on Hilf's results in terms of converted value of the parable peak (w^F_{opt}, $\gamma^F_{d\,max}$), the optimum water content and the maximum dry density of the integral material were obtained (w^T_{opt}, $\gamma^T_{d\,max}$) through the application of these corrective formulas.

In 1994, Torrey & Donaghe[9] defined two additional quantities: the density interference coefficient, I_c, and the optimum water content factor, F_{opt}, expressed as:

$$I_c = \frac{100F_F}{P_c G_M} \tag{5}$$

$$F_{opt} = \frac{100w^F{}_{opt}}{P_c w^T{}_{opt}} \tag{6}$$

where F_F is the fraction density factor given by $F_F = \gamma^F_d / \gamma^F_{d\,max}$, γ^F_d is the dry unit weight of the finer fraction and G_M is the soil particle density of the coarser fraction.

To calculate F_F, the following equation was used:

$$F_F = \frac{\gamma^T_{d\,max} G_M \gamma_w P_F}{100\gamma^F_{d\,max} G_M \gamma_w - \gamma^T_{d\,max}\gamma^F_{d\,max} P_C} \tag{7}$$

Table 5 presents the original and deduced equations in 2004 and 2008. These corrective equations were used to compare the results obtained in the construction control.

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 (4.75mm) fraction material (P_c) ranged between approximately 17% and 68%, with an average value of 49%.

Test	I_c	F_{opt}
Torrey & Donaghe [9]	$\log I_c = 1.614 - 1.025\log P_c$ $R^2 = 0.99$	$\log F_{op} = 1.812 - 0.730\log P_c$ $R^2 = 0.98$
Vibratory Compactions Tests (2004)	$\log I_c = 1.7398 - 1.0935\log P_c$ $R^2 = 0.9912$	$\log F_{op} = 1.8343 - 0.828\log P_c$ $R^2 = 0.9685$
Vibratory Compactions Tests (2008)	$\log I_c = 1.7371 - 1.0693\log P_c$ $R^2 = 0.9996$	$\log F_{op} = 2.3848 - 1.5805\log P_c$ $R^2 = 0.1$

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

Table 5. Original and deduced corrective equations

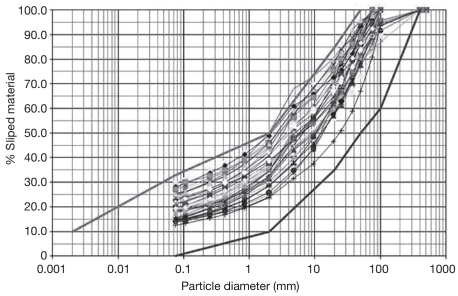
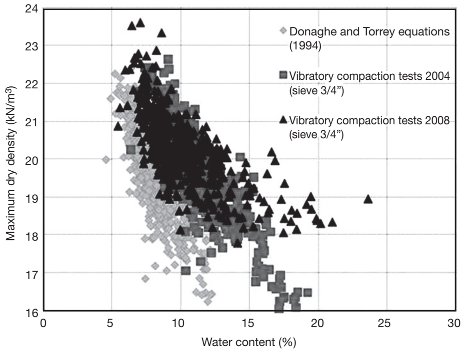


Figure 8. Grading size distribution curves from the Odelouca Dam upstream shell

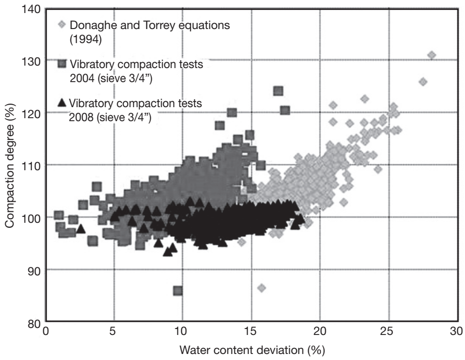
Both Figure 9 and Table 6 contain the results achieved with the application of the corrective equations to the values obtained with Hilf's method and its comparison with the field in the upstream shell of the Odelouca Dam compaction control in terms of water content deviation and compaction degree.

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 & Torrey[9] 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 the other hand, the variance was minimized considering the most recent laboratory tests.



(a)



(b)

Figure 9. a) Maximum dry density *vs* optimum water content; b) compaction degree *vs* water content deviation through the application of Hilf's method to the fine fraction in the upstream shell of the Odelouca Dam compaction control

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.

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

	Test	$\gamma^T_{d\,max}$ (kN/m^3)	w^T_{opt} (%)	Δw (%)	G_C (%)
Maximum Minimum Average Standard deviation Variance	Donaghe & Torrey[9]	24.8 14.0 19.2 1.3 1.8	15.3 4.6 8.3 1.7 2.8	7.2 0.6 3.2 1.1 1.2	131.0 86.5 105.0 4.8 23.3
Maximum Minimum Average Standard deviation Variance	Vibratory compaction tests (2004)	25.0 14.8 19.5 1.2 1.5	19.2 6.4 11.6 2.1 4.5	3.0 -3.0 0.0 1.0 1.0	124.1 85.8 103.4 4.0 16.1
Maximum Minimum Average Standard deviation Variance	Vibratory compaction tests (2008)	23.6 17.8 20.3 0.9 0.9	23.6 5.4 10.1 2.5 6.5	3.4 -3.0 1.5 0.9 0.8	103.1 93.4 99.5 1.5 2.3

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

6. CONCLUSIONS

This paper presents the results from an investigative laboratory study relative to the application 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 Hilf's method, developed for fine soils since it does not need previous knowledge of the materials' characteristics. Therefore, using materials from the Odelouca Dam's shells (weathered schist with a significant fraction of large size particles), the results from a laboratory study relating to the conditions of application and the applicability of Hilf's method to coarser soils and soil-rock mixtures have been presented.

A series of laboratory tests were performed using traditional and large-scale compactors, and different percentages of coarser fractions. The use of this large-scale compactor avoids truncation of the material grain size distribution curve, and the subsequent correction of the results. Some conclusions are drawn below regarding the applicability of this method:

1. Hilf's method is applicable to material passing through #4, 3/4" and 2" sieves.
2. It is also capable of correctly identifying the samples on both the wet and 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, with an error inferior to 0.01.

The compaction control of the Odelouca Dam's 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. Taking into account the oversized particles, corrective formulas were applied to these results in order to calculate the maximum dry density and optimum water content of the soil-rock mixture.

Based on the work of Torrey & Donaghe[9], several laboratory tests were carried out in 2004 during the execution of the cofferdam, and again in 2008 during the execution of the main dam, for the calibration of those corrective formulas. These new formulas, together with the originals, were applied to the compaction results of the upstream shells. These results were compared with those from the construction of the Odelouca Dam.

From the results obtained it can be concluded that the use of corrective formulas in soil-rock mixtures, which take into account the oversized particles, demands the execution of laboratory compaction tests throughout the construction period, and the deduction of the corresponding equations, in order to reflect the differences between the materials collected in the borrow areas over time.

Alternatively, this paper shows that Hilf's method can be applied directly if a large compactor is available with no truncation of the material gradation curve, rendering the quality control more accurate and easier to carry out.

ACKNOWLEDGMENTS

The authors of this paper would like to thank the owners of Odelouca Dam, Águas do Algarve, for their contribution to the present work, particularly for making available the materials for the tests. We would also like to express our gratitude to the LNEC technicians, especially António Cardoso and Joaquim Timóteo, for the development of the experimental work.

REFERENCES

[1] Hilf, J, '*A Rapid Method of Construction Control for Embankments of Cohesive Soil*', Engineering Monograph No 26, Bureau of Reclamation, p23, (1959).

[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, Portugal, (1966).

[6] American National Standard, '*ASTM - D698-00a. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12.400ft-lbf/ft3 (600kN^{-3}/m^{3}))*', (2000).

[7] '*USBR 5515-89. Procedure for Performing Laboratory Compaction of Soils Containing Gravel*', US Department of the Interior, Bureau of Reclamation, Denver, CO, US, (1989).

[8] Brito, A, 'Compactação de Aterros de Barragens. Novas Metodologias de Controlo', *Dissertação de Mestrado*, Instituto Superior Técnico, Universidade Técnica de Lisboa, (2006).

[9] Torrey, V H & Donaghe, R T, '*Compactions Control of Earth-rock Mixtures: A New Approach*', Vol 17, Issue 3, (1994).