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Application of hydraulic cylinder testing to determine the geotechnical properties of earth-filled dams

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Abstract. This article describes a new in-situ load test called the Hydraulic Cylinder Test (HCT) and its application to determine the geotechnical properties of soil-rock mixtures. The main advantages of the test are its easy implementation, speed of execution and low-cost. This article provides a detailed description of the equipment and the test procedure, and examines a case study of its application to determine the geotechnical properties of an earth-filled dam for a tailings pond. The containment dams of the ponds are made from blocks of gypsum and marl, obtained from the excavation of the ponds, mixed in a matrix of sands and clays. The size of the rocks varies between 1 and 30 cm. The HCT is particularly useful for determining the geotechnical properties of this type of soil-rock mixture. Nine HCTs were carried out to determine its strength (c, ϕ) and deformation (B, G) properties. The results obtained were validated using the Bim strength criterion, recently proposed, and some pressure meter tests carried out beforehand. The properties obtained are used to analyze the stability of the dam using computer simulations and a modification to its design is proposed.

Keywords: hydraulic cylinder test (HCT); earth-filled dams; soil-rock mixture; bim strength criterion; back analysis

1. Introduction

Earth-filled dams used in the construction of tailings ponds and reservoirs are often built from materials obtained during the excavation of the pond or, where this is not possible, aggregates from nearby quarries.

Borrow earth is placed and spread generally in 30-cm-thick lifts before compaction using rollers. The man-made compacted fills are heterogeneous, largely due to the difficulties in finding a homogeneous borrow source to complete the whole project. In order to overcome potential

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quality control issues caused by the variability of the material in the borrow source, proctor tests are performed on all the different materials to create a family of proctor curves before construction of the compacted earth fills. The curves and the associated material types, together with visual descriptions, are used as an aid by field technicians to check the quality of the compaction based on the relative compaction value given in the project specifications. In addition to the proctor tests, triaxial strength tests are also carried out on borrow materials to determine the Mohr-Coulomb parameters during the design stage. Triaxial specimens are prepared in the lab with a density corresponding to the relative compaction value (the minimum compaction criteria for the as-built compacted fills). The strength parameters for the minimum compaction criteria are used in the design stage for stability calculations. All possible varieties of materials used in the project are characterized during the design stage for use by the technicians during field inspections for compaction quality control.

For cases in which the dam is built from blocks of rock that are incorporated into a finer matrix, the aforementioned procedure is not the most suitable. In this case, it is only possible to test the matrix at laboratory scale and hence, some type of in-situ testing must be carried out for the joint analysis of the rock and the matrix. During construction of the dam, the most common test is the plate-loading test (Ünal 1997, Pells 1983) to evaluate the compaction of the different layers of soil.

Upon completion of the dam, supplementary tests, such as drilling boreholes and the use of pressure-dilatometers, can be used to analyze the deformation properties of the soil (Briaud 1992, Clarke 1995). Penetration tests, such as the Cone Penetration Test (CPT) (Campanella and Robertson 1981) and Dilatometer Test (DMT) (Marchetti 1980) are widely used to measure in situ the strength properties of soil. These devices are often combined with seismic modules (i.e., SCPT (Schneider *et al*. 2001), SDMT (Castelli and Maugeri 2014, Marchetti 2014).

Further to these conventional testing methods, in the last years other alternative technologies have been developed.

Ramírez-Oyanguren *et al*. (2008) analyzed the stability of a rockfill dam by means of an in situ direct shear test. The test is similar to the direct shear laboratory test for soils and allows testing large-size samples. In the same way, Fakhimi *et al*. (2008) designed a modified direct shear test apparatus to measure cohesion and friction angle of rock pile materials. The main difference between the in situ shear box and its conventional laboratory equivalent is that the in situ shear box consists of a single box that confines an excavated block of rock pile material.

Coli *et al*. (2011) developed a non-conventional in situ shear test apparatus to investigate the strength properties of a bimrock, by taking into account the influence of the blocks, and to overcome the size limitation of laboratory specimens. The testing procedure is inspired by that described by Li *et al*. (2004) and Xu *et al*. (2007).

Wen-Jie *et al*. (2011) used a digital image processing (DIP) to obtain the proportion and distribution of the rock blocks in a soil-rock mixture (S-RM). The results were used for the sample preparation of large scale direct shear tests. According to the results, the rock block size proportion controls the deformation and fracture mechanism of the S-RM.

Kowalczyk *et al*. (2014) studied the relation between the electrical resistivity of non-cohesive soils and its degree of compaction.

More recently, Kalender *et al*. (2014) proposed an empirical Bim strength criterion for predicting the overall strength of unwelded bimrocks and bimsoils.

To complement these techniques, the Ground Engineering Research Group at the University of Oviedo has developed the equipment and test procedure for the Hydraulic Cylinder Test (HCT), which can be used to determine the strength and deformation parameters of heterogeneous soils and man-made fills. The execution of the test is extremely simple and only requires the excavation of a trench. The potential of this technique has already been proven in determining the characteristics of highly fractured rock masses (Gonzalez-Nicieza *et al*. 2013).

This article provides a detailed description of the equipment that has been designed and the proposed test method to determine the strength and deformation properties of the materials that are tested. A practical example is also given based on determining the characteristics of the structure of a containment dam for a tailings pond. The strength and deformation properties that are obtained are used to analyze the stability of the dam using computer simulations and a modification to its design is proposed.

2. The Hydraulic Cylinder Test (HCT)

The Hydraulic Cylinder Test is a load test that works by using a hydraulic cylinder to apply pressure to the soil until it fails. The operating principle is similar to the static plate-loading test, although in the HCT the load is not transmitted vertically but is applied perpendicular to the walls of the trench that has been excavated (Fig. 1).

The test procedure begins with the excavation of a trench in the soil to be tested using a hydraulic excavator. The hydraulic cylinder is then placed in the trench, perpendicular to the walls. A hydraulic power unit is then used to pump oil into the cylinder and the pressure is transmitted to the soil using a circular steel plate fitted to the end of the piston. The diameter of the plate is variable and is chosen after visually examining the stratum to be tested (Fig. 2). Larger distribution plates will be used for more heterogeneous soils or larger aggregates, making it possible to test both the larger rocks and the matrix at the same time, obtaining more representative results than would be possible with laboratory testing, where it is only possible to test the matrix of the soil. The hinge joint at the end of the piston, where it is joined to the plate, ensures the load is correctly applied to the soil.

The hydraulic power unit uses an A10VSO hydraulic axial piston variable pump that can transmit a maximum pressure of 25 MPa. There is also a control unit to regulate the pressure and

Fig. 1 Testing using the HCT

(a) (b) (c)

Fig. 2 Applying pressure to the tested soil using different sizes of plates

(a) (b) (c)

Fig. 3 (a) Hydraulic power unit; (b) Electrical switchboard and data capture system; (c) Connection to computer

direction of the piston movement. The hydraulic cylinder is equipped with pressure and movement sensors, whose data is stored in the control unit. This unit is connected to a computer with a data capture card, allowing the pressure-displacement curve to be observed in real time while the test is being carried out (Fig. 3).

Once the pressure–displacement curve has been obtained, it is possible to determine the failure pressure, residual pressure and penetration of the cylinder in the soil until failure occurs (Fig. 4). Four different phases can be distinguished: a first phase or horizontal area, which corresponds to the stroke of the piston until the hydraulic cylinder enters into contact with the trench walls (cylinder-trench coupling), which constitutes the second phase; a third phase or ascending inclined area, which represents the zone in which the hydraulic cylinder is exerting pressure on the trench walls (a phase during which the material behaves elastically); and, finally, the fourth phase, which corresponds to failure of the ground.

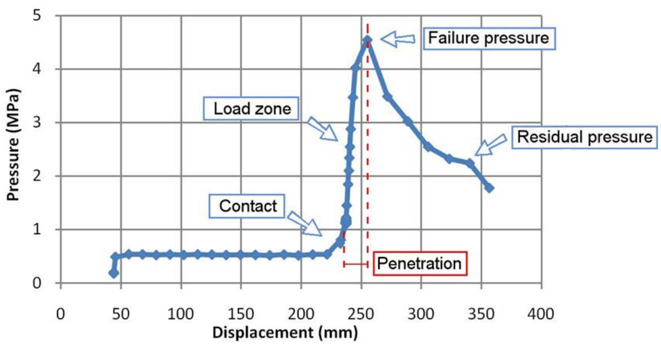

Fig. 4 Graph obtained from a HCT

Back analysis techniques are then used to obtain the strength and deformation parameters of the soil. To do so, a 3D model is created to reproduce the geometric conditions of the test (dimensions and depth of the trench and position of the equipment inside it) and the lithostratigraphic properties of the soil, indicating the position and dip of the various strata. For the case in question (earth-filled dams) the models are often constructed from a single material (the aggregate used in the construction of the dam) and only indicate the position of the rock substratum when this is close to the test zone. For this purpose, the FLAC 3D software is used (Itasca 2005) and Fig. 5 shows the model created to simulate an HCT inside a trench. The red cylinder represents the distribution plate fitted to the head of the cylinder.

After the geometry of the model has been created, the estimated cohesion and friction angle obtained from other studies and field work are input, together with the deformation moduli for the soil (the Bulk modulus and shear modulus). These are the parameters required to analyze the soil behavior using the Mohr-Coulomb model. The effect of the drive of the piston is then simulated in the model. Fig. 6 shows a cross section of the model similar to the previous one in which the distribution plate has been removed to better show the distribution of stresses.

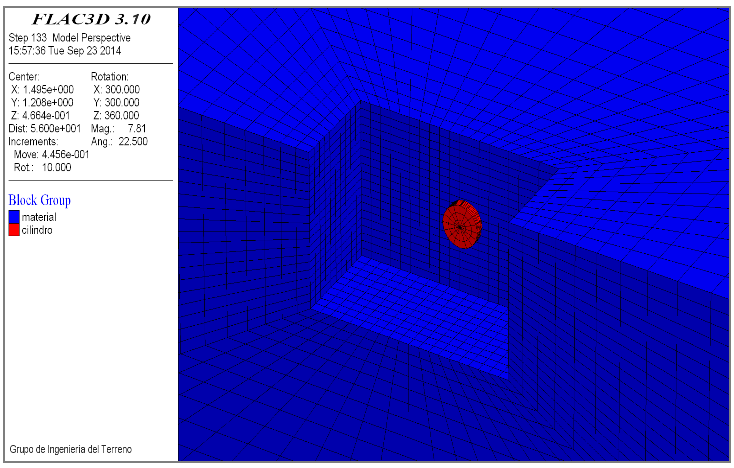

Fig. 5 3D mesh of the calibration model

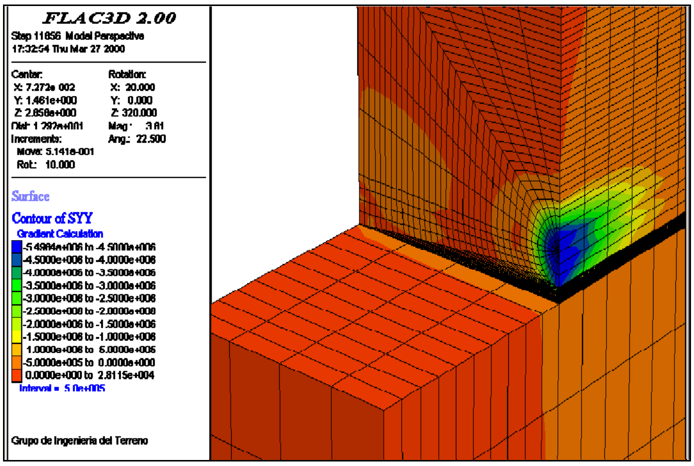

Fig. 6 Simulation of applied pressure

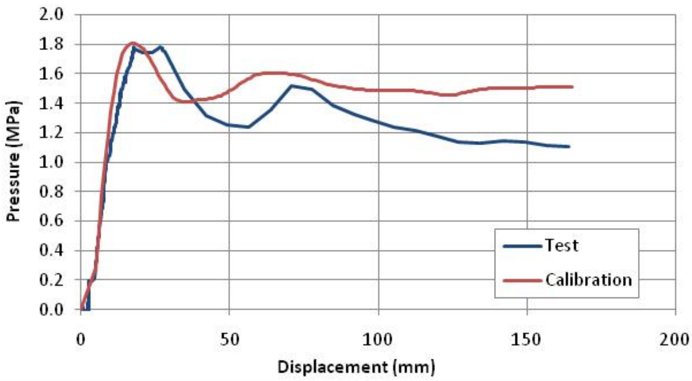

Fig. 7 Example of calibration

This gives the theoretical pressure-displacement curve. The calculations are then repeated; adjusting the initially estimated values to bring the theoretical curve obtained using the numeric simulation closer to the real curve obtained from the HCT.

In general terms, the deformation moduli determine the gradient of the curve and strength, cohesion and friction angle determine the pressure of failure. When the two curves have been fitted, it is assumed that the values entered into the model are close to the real ones (Fig. 7). This gives the values for the cohesion, friction angle, Bulk modulus (K) and the shear modulus (G).

Once the test has been calibrated, it is possible to obtain the Young's modulus (E) and the Poisson coefficient (ν) from equations Eqs. (1)-(2).

$$K = \frac{E}{3 \cdot (1 - 2\nu)} \tag{1}$$

$$G = \frac{E}{2 \cdot (1 + \nu)} \tag{2}$$

3. Determining the characteristics of a earth-filled dam using the HCT

This section analyses an increase to the dam at a mine in the province of Cordoba in southern Spain. After minerals have been extracted and concentrated in a flotation plant, the tailings are stored in various tailings ponds. The containment dams of the ponds are made from gypsum and marl rock obtained from the excavation of the ponds. The size of the rocks varies between 1 and 30 cm. During construction of the dams, the materials were mixed in a matrix of sands and clays to provide consistency before being compacted in lifts of variable thickness. The upper part includes a layer of gravel and sand at the level of the road for the circulation of vehicles.

It is necessary to increase the capacity of one of the ponds by increasing its height by 5 m. The new dam construction will use the granulometric fraction below 4 mm of the leavings proceeding from the crushing and flotation process for the mineral. Fig. 8 shows the current profile of the dam, together with the proposed increase.

To determine if the proposed design is stable and analyze the feasibility of this project, it is necessary to first know the strength and deformation properties of the materials of the dam itself and the foundation on which the structure will be built.

There is, however, no information about the tests carried out during the construction of the dam and there is only limited data from a research project undertaken some years back when the dam had been built. Table 1 shows the tests carried out and the results obtained.

The report on the tests carried out states that the identification tests correspond to the matrix in which the blocks of gypsum and marls were incorporated. The table shows that the tests were

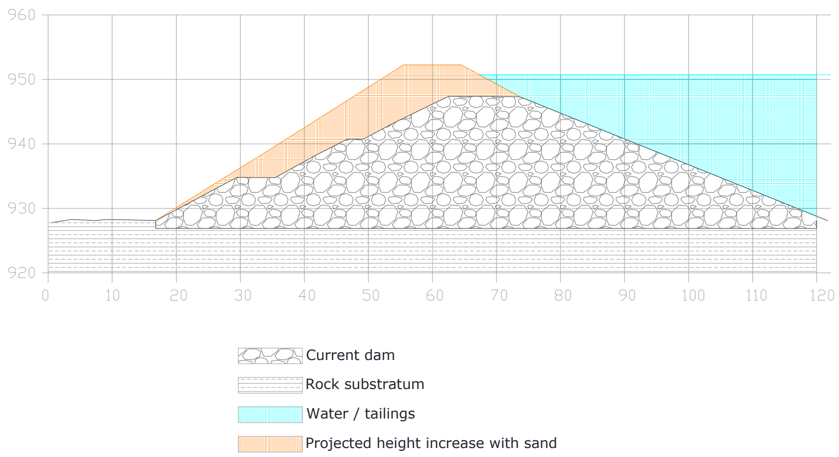

Fig. 8 Dam under study

Table 1 Tests results for the dam

Laboratory tests – USCS classification	Id1	Id2	Id3	Id4	Id5
	CL	CL	CL	ML	CL
In-situ pressure meter tests	PD1	PD2	PD3	PD4	PD5
E_p – Pressure meter modulus (MPa)	14.7	3.9	-	-	-
G – Shear modulus (MPa)	5.2	1.5	-	-	-

Table 2 Test results for the sands

Laboratory tests – direct shear	CD1	CD2	CD3	CD4
c – Cohesion (kPa)	7	15	19	18
ϕ – Angle of repose (°)	28	20	20	21

In-situ pressure meter test	PD1	PD2	PD3
E_p – Pressure meter modulus (MPa)	2.1	3.5	2.8
G – Shear modulus (MPa)	0.8	1.3	1.1

insufficient to correctly determine the characteristics of the dam. The pre-bored pressure meter (PBP) tests that were carried out and their results are insufficient. The nature of the soil (blocks of rock incorporated in a matrix of fines) means that the walls of the boreholes made for these tests are of poor quality. There is no smooth, homogeneous surface on which to apply the load. As a consequence, only two of the five attempts were acceptable. The difference in the results is due to the heterogeneity of the dam. Similarly, during the drilling of the boreholes, attempts were made to carry out two SPTs, both of which were rejected when they met blocks of rock.

In the same geotechnical work, similar sands to the ones that will be used in increasing the dam were tested. These are mainly SM and SC sands (USCS classification). The tests were carried out on another dam nearby that belongs to the same company. Table 2 shows the tests carried out and the results obtained.

In order to improve characterization of the dam body, nine HCT tests have been carried out to estimate its strength and deformation properties. Two additional tests have been carried out on the sands that will be used to increase the height of the dam. Furthermore, the properties of the foundation (gypsums and marls) are known and have been provided by the company that owns the tailings ponds.

3.1 Determining the properties of the dam

The dams of the ponds are made up of blocks of gypsums and marls between 1 and 30 cm. These are mixed into the clayey-sandy matrix and are compacted in lifts.

Table 3 Results of HCTs on the dam

Test	*P* (MPa)	*c* (kPa)	ø (˚)	*K* (MPa)	*G* (MPa)	*E* (MPa)
D1	1.2	20	23	5.0	2.3	6.0
D2	1.8	38	40	2.5	1.2	3.0
D3	1.7	20	37	5.2	2.4	6.2
D4	1.6	15	37	4.0	1.9	4.8
D5	0.9	20	24	2.0	0.9	2.4
D6	0.9	13	21	6.5	3.0	7.8
D7	1.2	20	28	3.0	1.4	3.6
D8	0.9	20	30	0.9	0.4	1.1
D9	1.2	20	30	5.5	2.5	6.6
Average value	1.3	20.7	30	3.8	1.7	4.6

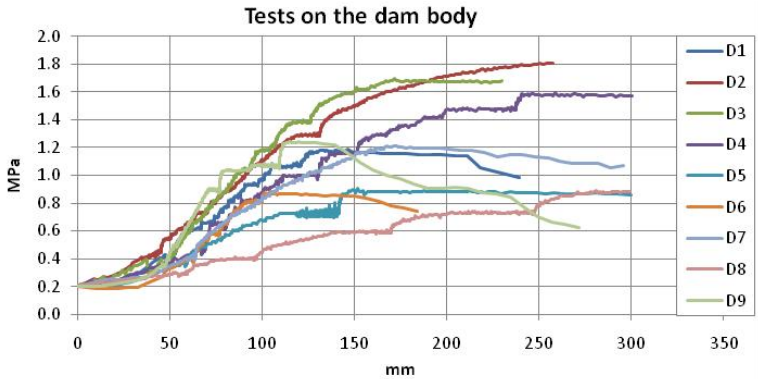

Fig. 9 Tests on the dam body

The pressure meter tests carried out beforehand provided a range of results, possibly because the tests have been carried out on different materials due to the heterogeneity of the dam (see Table 1).

The HCT is particularly useful for determining the properties of this type of soils.

To improve the characterization of the dam, nine HCTs were carried out, all of which used a 45 cm diameter distribution plate. Table 3 shows the failure pressure (*P*) obtained in the nine tests. The strength (*c* and ø) and deformation (*K* and *G*) parameters obtained after calibration are also included. The value of the Young's modulus (*E*) has been calculated as 0.3 using the Poisson coefficient.

Fig. 9 shows the curves obtained for the tests. There is variation in the failure pressures and gradients of the elastic section. As all the tests were carried out at the same depth and under the same conditions, this variability cannot be attributed to the test method. It is possible that the variations in the results are due to the heterogeneity of the dam (variations in the proportion of blocks of rock and the matrix between tests).

Comparing the values in Tables 3 and 1, it is clear that the values of *G* obtained using the HCTs and the value obtained in the pressure meter test PD2 are in the same range. The value obtained for test PD1 is higher than that obtained in the HCTs. As previously mentioned, this can be attributed to the heterogeneity of the soil. Test PD1 was probably carried out in a zone with larger blocks or where there were a higher proportion of blocks of rock with respect to the matrix.

3.2 Testing the reliability of HCT tests using the Bim strenght criterion

Recently Kalender *et al*. (2014) proposed a new empirical criterion for predicting the overall strength of unwelded bimrocks and bimsoils. The Bim strength criterion is based on empirical equations proposed by Sonmez *et al*. (2009) (Eqs. (3)-(5)).

$$\phi_{bimrock} = \phi_{matrix}\left[1 + \frac{1000\left[\left(\alpha/\phi_{matrix}\right)-1\right]}{1000+5^{((1-VBP)/15)}} \cdot \frac{VBP}{VBP+1}\right] \tag{3}$$

$$UCS_{bimrock} = \frac{(A - A^{(VBP/100)})}{(A-1)} \cdot UCS_{matrix} \qquad 0.1 \Leftarrow A \Leftarrow 500 \tag{4}$$

$$c_{bimrock} = \frac{UCS_{bimrock} \cdot (1 - \sin(\phi_{bimrock}))}{2\cos(\phi_{bimrock})} \tag{5}$$

In Eqs. (3)-(5), $\phi_{bimrock}$ and ϕ_{matrix} are internal friction angle of bimrock and internal friction angle matrix in degrees, respectively; α is the angle of repose for blocks in degrees; $UCS_{bimrock}$ and UCS_{matrix} are uniaxial compressive strength of bimrock and matrix respectively; $c_{bimrock}$ is the cohesion of the bimrock; VBP Volumetric Block Proportion as percentage; "*A*" depends on the boundary properties between block and matrix.

To calculate the cohesion and friction of the dam according to these equations it is necessary to know the VBP on the dam, the friction angle of the clay matrix, the compressive strength of the matrix, the angle of repose of the blocks and the value the "*A*" parameter.

First it has been calculated the volumetric block proportion (VBP). Based on the observations made in situ during the execution of the tests HCT, and subsequent analysis of the photographs made in the trenches and material piles from excavation, it has been estimated the VBP value between 40 and 60% depending on the dam area (Fig. 10).

The average angle of repose for blocks is 34°.

Since no specific tests were performed to calculate the friction of the clay matrix, this value was estimated according to the literature. According to Spanish standard DB SE-C "Structural Safety: Foundations", typical friction angle for a CL clay can vary between 16 and 28°.

Fig. 10 Material piles from excavation. VBP variation

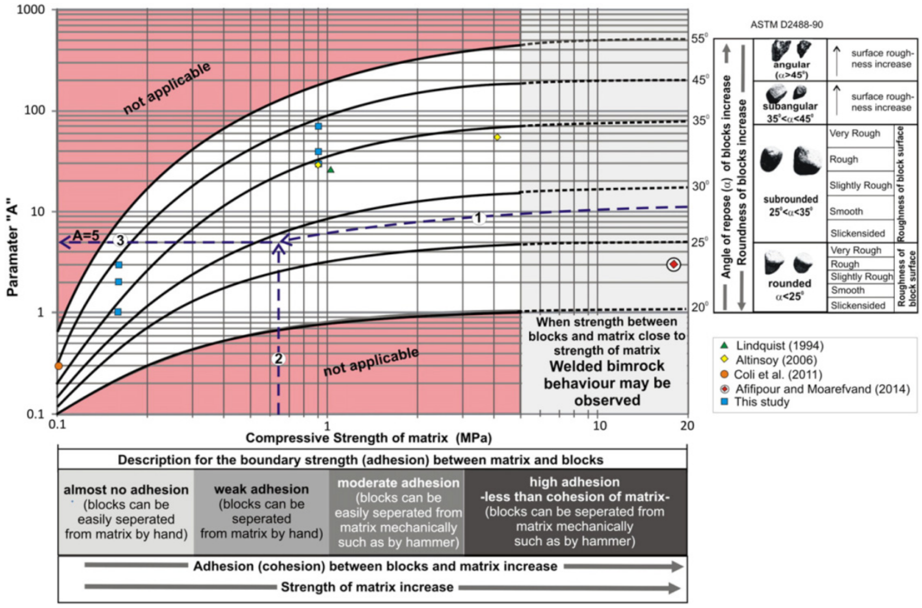

Fig. 11 Practical guide for the selection of "*A*" (Kalender *et al.* 2014)

Table 4 Dam strength from Bim strength criterion

VBP (%)	ϕ_{matrix}	$c_{bimrock}$ (kPa)	$\Phi_{bimrock}$ (°)
40	16º	21.4	27.4
	28º	19.4	32.2
50	16º	18.4	31.3
	28º	17.5	33.7
60	16º	15.8	33.4
	28º	15.5	34.4

In this document it is also indicated that the compressive strength of this type of clay is between 0.05 and 0.1 MPa.

Finally, "*A*" was calculated according the practical guide proposed by Kalender *et al.* (2014), obtaining a value of 20 (Fig. 11).

Table 4 shows the results obtained from application of Eqs. (3)-(5) in terms of the VBP and internal friction angle of matrix (variable between 16° and 28°). In these calculations it has been estimated a compressive strength of matrix of 0.08 MPa.

Average value from HCT tests (21 kPa cohesion and 30º friction) are very close to the results from Table 4. The properties obtained by such different methods are very similar. Therefore, it is possible to say that the results are quite accurate and remarkably close to the real properties of the dam.

3.3 Determining the properties of the sands used to growth the dam

The granulometric and identification analyses carried out on these materials indicate they have

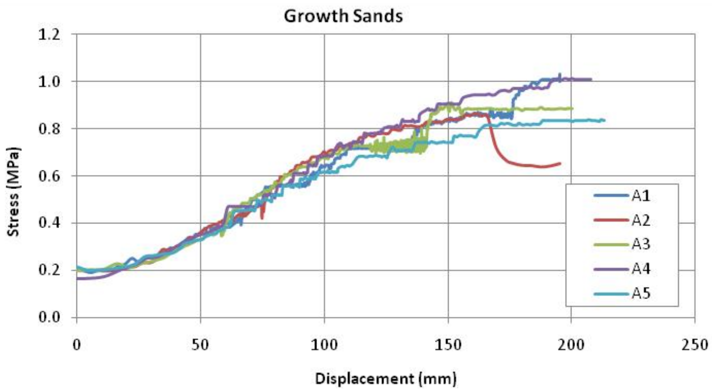

Fig. 12 HCTs on the sands for increasing the dam

Table 5 Results of HCTs on the sands

Test	*P* (MPa)	c_u (kPa)	ø (°)	*K* (MPa)	*G* (MPa)	*E* (MPa)
A1	1.0	16	24	2.0	0.9	2.4
A2	0.8	15	20	3.0	1.4	3.6
A3	0.9	20	24	2.0	0.9	2.4
A4	1.0	15	21	2.5	1.2	3.0
A5	0.8	12	22	2.8	1.3	3.4
Average value	0.9	15.5	22	2.5	1.2	3.0

a poor classification and their fine fraction corresponds to CL clays (USCS classification). During the geotechnical work prior to the HCTs, four direct shear tests were carried out in the laboratory, as well as three pressure meter tests (see Table 2). To complete these tests and improve the characteristics of these materials, five HCTs were carried out with the 45 cm diameter distribution plate.

Fig. 12 shows the curves obtained for the HCTs. All the curves are highly similar, indicating a high level of homogeneity in the behavior of the material. Table 5 shows the values obtained following calibration of the tests.

The average value of the shear modulus (*G*) obtained using the HCTs are highly similar to the average value of the pressure meter tests carried out previously (1.1 MPa). On the other hand, if the cohesion and friction angle values obtained after calibration of HCTs are compared to those resulting from direct shear tests in laboratory (Table 2), very similar values are observed.

It can be stated that HCT results are coherent with the strength parameters obtained in direct shear tests in laboratory and with the value of the shear modulus obtained in the pressure meter tests.

4. Analysis of the stability of the proposed design

Once the properties of all the materials are known, the proposed design for increasing the height of the dam was analyzed for stability. For this purpose, the SLOPE computer program, developed by the Canadian company GEO-SLOPE International, was used (Geo-Slope 2004). The stability analysis was based on the calculation of the safety factor for possible slides that may occur along a given profile.

Seven profiles along the dam perimeter have been studied. In specific terms, the following profiles were chosen (shown in pink in Fig. 13): 0, 150, 250, 350, 475, 600 and 700.

The strength values obtained from the calibrations of the HCTs have been used for both the dam and the sands that will be used to increase its height. The values provided by the company that owns the ponds were used for the foundation. Table 6 shows the properties used for each of the materials in the calculation.

In terms of the tailings in the pond, the values of cohesion and friction have been estimated based on the assumption that they are not solidified and that the pond contains a fluid paste.

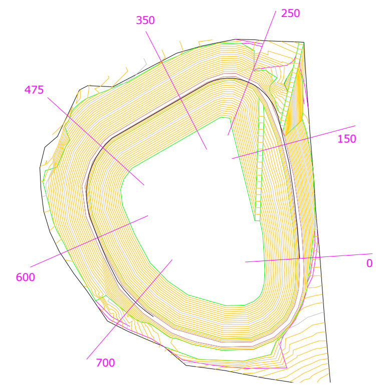

Fig. 13 Design of the dam and selected profiles

Table 6 Properties used in the SLOPE calculations

Material	Density (kN/m³)	Cohesion (kPa)	Friction Ø (˚)
Tailings	18	0	6
Current dam	20	21	30
Sand for the growth	20	16	22
Foundation – gypsums	25	35	23

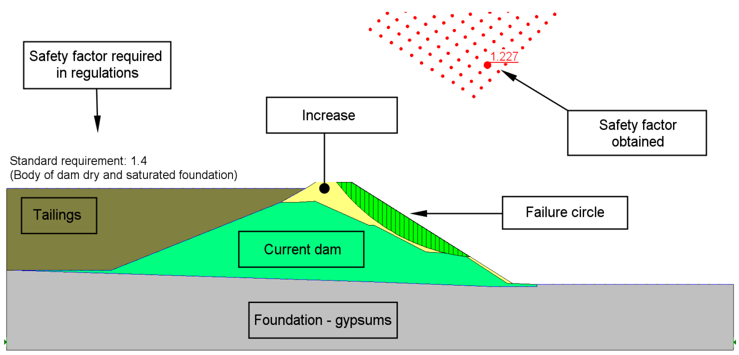

Fig. 14 Safety factor of the failure circle

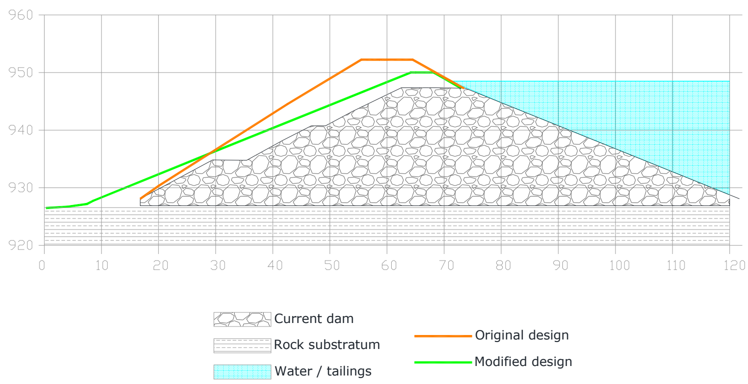

Fig. 15 Modified design

Spanish technical regulation (ITC 08.02.01 2001) has been used to determine the minimum safety factor required to guarantee the long-term stability of the dam.

The majority of the profiles that have been analyzed comply with the aforementioned regulation, which requires safety factors in excess of 1.4 under normal conditions (full pond, dam body dry and foundation fully saturated). However, in the zone where the dam reaches its greatest height (profile 475), the tests carried out show the presence of small circles of failure that only affect the increased zone. In these cases, the safety factor is below the required level (see Fig. 14).

Consequently, it is necessary to make a new design for the growth of the dam. To guarantee the long-term safety of the dam it has been also analyzed what are the riskiest factors to its stability: dam body partially saturated and seismic acceleration of 0.26 (earthquake acceleration in this site based on the Spanish standard NCSE-02). Subsequently, according with the aforementioned regulation ITC 08.02.01 (2001), it was established that the minimum safety factor in this extreme situation should be 1.2.

After several simulations it was concluded that, to achieve this objective, it is necessary to reduce the height of the dam at 2.5 m from the original design and bring down the slope angle as shown in Fig. 15.

5. Conclusions

The HCT is a particularly useful test for determining the characteristics of heterogeneous soils that are difficult to characterize using conventional tests, like soil-rock mixtures. It is a quick and easy test. It requires only a hydraulic excavator as auxiliary machinery to dig trenches where tests are done.

The HCTs carried out on the dam made it possible to improve its characterization and determine its strength (c, ϕ) and deformation (B, G) properties.

The results from the application of the Bim strength criterion proposed by Kalender *et al.* (2014) to the dam matches with those obtained in the HCTs. Since the results obtained by such different methods are very similar, it is possible to say that the results are quite accurate and remarkably close to the real properties of the dam.

The properties obtained were used to analyze the stability of the dam using SLOPE software. The stability study that was carried out shows that the proposed design for increasing the height of the dam does not meet the required safety criteria. An alternative design was proposed to guarantee the long term safety of the dam.

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