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Effect of the construction procedure on the dynamic behaviour of the clay in the core of an earth dam

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ABSTRACT: The purpose of this article is to compare the dymanic behaviour expected for the Canales Dam based on the project data, with the actual behaviour based on data obtained from undisturbed samples taken from the core of the dam after construction. By doing this, it has been possible to assess the effect that the construction procedure has had upon core response during an earthquake. Given that a clay with a high degree of plasticity has been used, an attempt has also been made to evaluate the effect that the irregularity of the load might have on the degradation process of the mechanical characteristics of the material subject to dymanic seismic input conditions. In order to do this, peak to peak axial strains obtained in cyclic triaxial tests with both types of sample subjected to the same irregular stress history that was calculated at the dam for a design earthquake, were compared to those determined after 30 cycles of equivalent load with a frequency of 1Hz.

1. INTRODUCTION

When numerical analyses are made to determine the dynamic behaviour of an earth dam at the design stage, prior to its construction, all the laboratory tests that are required to characterize the behaviour of the core are carried out with material taken from quarries and compacted to density and moisture conditions as close as possible to those specified in design.

Therefore, it is useful to be able to know and quantify numerically, the differences in response, under earthquake-type loadings between the material tested in the laboratory at the design phase of the dam, and the same material tested in the conditions obtained with the procedures and machinery actually used in building the dam.

On the occasion of the construction and operation of the Canales earth dam, the dynamic behaviour of the core material determined before the construction, with samples compacted to the design conditions, has been compared with that obtained using specimens trimmed in undisturbed samples taken from the dam after construction had been completed.

2. DESCRIPTION OF THE MATERIAL

The material which constitutes the dam core, belongs to a Miocene formation lying close to the site. It is a grey clay with a high degree of plasticity (LL = 60-70 and PI = 35-45) which, when compacted to standard Proctor conditions (γ_D = 16 kN/m^3, h = 20%), swells up to 10-15% on being saturated in edometric conditions under a nominal load of 10 kPa, and is capable of developing swelling pressures ranging from 200 to 400 kPa.

It is mainly composed of mica and montmorillonite, and to a lesser extent kaolinite, quartz and calcite.

It has a calcium carbonate content of about 25% and a sulphate (SO_3) content of between 0.5 and 4%.

The tests carried out to find out the specific weight of the particles, have provided a representative value of 27.3 kN/m^3.

To prevent the material extracted from the quarry from becoming too dry, it was stocked and wetted from time to time; this gave rise to the formation of hard nodules with sizes of between one and two centimetres only a few of which were broken up by the methods used to put the materials into place. Gypsum crystals of different sizes and variable distribution were present inside the clay mass, and this also contributed to giving a certain degree of heterogeneity to the final product. The nodules and gypsum crystals lodged in the clay are thought to play an important role in the mechanical behaviour of the core.

3. TYPES OF SAMPLES USED

The tests, made to characterize the dynamic properties of the material, were carried out with two types of samples, "compacted" and "trimmed".

The "compacted" samples consist of material taken directly from the quarry, thoroughly ground up so that no lumps remained and then passed through nº 200 seive of the A.S.T.M. series. With a view to reproducing project conditions, the material was compacted into layers with the same energy as that used in standard Proctor tests. Dry densities ranging from 15.5 kN/m^3 to 16.5 kN/m^3 and water contents between 17 and 22% were thus obtained.

The second sample-type was obtained by trimming the undisturbed samples retrieved from several boreholes that were made in the dam core with rotary drillings, the boring fluid pressure being kept to a minimum. Sampling was done with stationary piston samplers. The maximum depth reached was 55 m. The dry density of these samples ranged from 17 to 19 kN/m^3 with water contents between 15 and 20%. The presence of gypsum crystals and nodules, with sizes of about 1 mm. and 20 mm.respectively, could be clearly observed in this type of samples.

4. RESULTS OBTAINED

4.1. G_{MAX} modulus

Resonant column tests with samples 38 mm. in diameter and 76 mm. high, showed that the material was highly sensitive to slight variations in the void ratio. Table 1 shows the G_{max} values obtained for different samples saturated and consolidated under a confining pressure of 100 kN/m^2.

It can be demonstrated that the values for the "trimmed" samples lie well below the correlation suggested by Hardin and Black (1986), and are close to that proposed by Lo Presti (1990). In the light of these correlations, the value for a dry density of 16 KN/m^3 (e=0.706), representative of the set of "compacted" samples, is too low.

Tests in which the effective confining pressure and the void ratio were kept virtually constant once the primary consolidation process of the material had been completed, have shown evidence of an increase in the G_{MAX} modulus per logarithm cycle of time ranging from 10 to 20% of the value obtained at the end of the primary consolidation process.

Table 1. Elastic shear modulus obtained for σ'_o = 100 kN/m^2

Type of sample	Dry unit weight	Void ratio	G_{max} (Mpa)
Trimmed	17.5	0.570	55
"	17.0	0.613	45
"	16.8	0.628	35
Compacted	16.0	0.706	20

4.2. Parameters G/G_{max} and D

Figures 1 and 2 show the variation of the modulus ratio G/G_{max} and the damping ratio D with the amplitude of the shear strain for "trimmed" samples that were tested under confining pressures of 300 and 400 kPa. The same figures also show (with unbroken lines) the curves

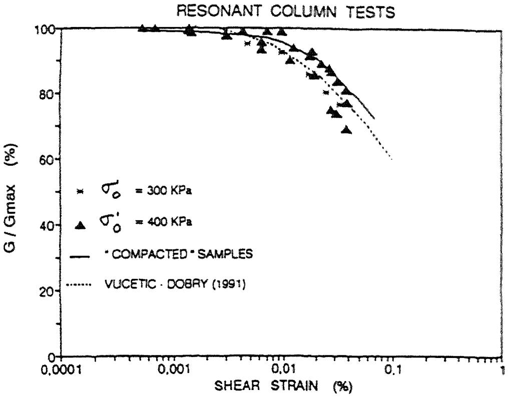

Figure 1. Shear modulus ratio versus shear strain for "trimmed" samples

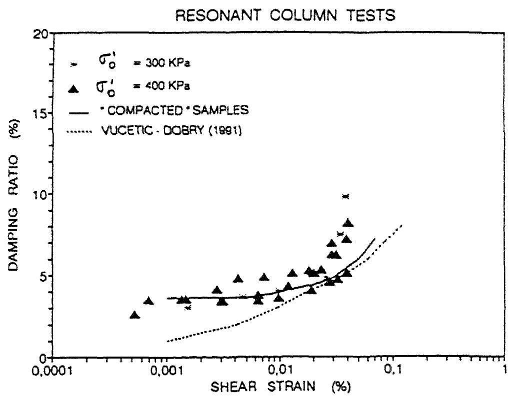

Figure 2. Damping ratio versus shear strain for "trimmed" samples

which represent the "compacted" samples that were tested under confining pressures of 100, 300, 500 and 800 kN/m^2. There is a high degree of consistency between the data obtained using either of the two sample-types that, regardless of the confining pressure , define one single curve for G/G_{MAX} and another for D. A shear strain threshold can be identified at 5 x 10^{-5}, above which the behaviour of the material ceases to be elastic. By way of comparison, these figures also include the curves recently suggested by Vucetic and Dobry (1991) for representing the behaviour of clay with a Plasticity index of 40.

5. CYCLIC STRENGTH

5.1. Uniform loading tests

26 cyclic triaxial tests (15 with "compacted" samples and 11 with "trimmed" samples) were carried out with a view to determining the degradation properties of the material. In the triaxial cell, the samples were subjected to stress

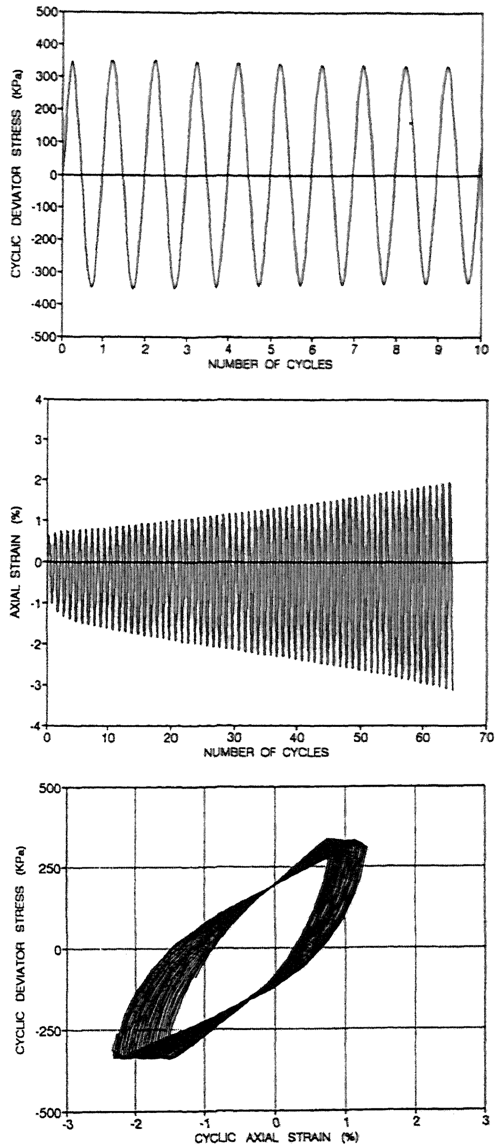

Figure 3. Stress controlled cyclic triaxial test run under 1 Hz frequency with a "trimmed" sample (γ_D = 1,85 k N/m^3), σ_o' = 500 kN/m^2

controlled deviator histories which varied in a senoidal way with a frequency of 1 Hz and the peak to peak axial strain caused in each cycle was measured.

The samples, all of which had a diameter of 50 mm. and a height of 100 mm., were saturated and isotropically consolidated under different confining pressures for periods never less than 48 hours.

A hydraulic servocontrol system activated at a pressure of 280 bars, was used to carry out the tests. Both the load cell and the LVDT transducer were placed inside the triaxial cell used to saturate and consolidate the samples. The data resulting from the tests, were recorded and processed in real time with two control terminals, a GA-600 General Automation computer and a graphic printer.

For illustrative purposes, Figure 3 shows the load and strain histories, and the hysteresis loops for a test carried out on a "trimmed" sample consolidated under a confining pressure of 500 kN/m^2.

Figure 4 shows for different confining pressures, the curves which provide, for each shear stress amplitude imposed in the tests, the number of cycles to which it has been necessary to subject the "trimmed" samples in order to obtain peak to peak axial strains between 2 and 5%. The curves for the "compacted" samples have been obtained in a similar way.

The graph in Figure 5 has been obtained by selecting from those figures, the amplitude of shear stress that causes the peak to peak strain values indicated after 30 load cycles for each confining pressure this graph clearly shows an increase in the strength of the "trimmed" samples with respect to the "compacted" ones.

5.2. Irregular loading tests

With a view to checking the influence that the irregularity of the seismic loads may have on the degradation behaviour of the material, two more laboratory tests were carried out: one with a "compacted" sample (γ_D = 16 kN/m^3) and the other with a "trimmed" sample (γ_D = 17.6 kN/m^3).

For the two cases, an attempt was made to reproduce the consolidation conditions and the irregularity both in amplitude and frequency of the shear stress history calculated for the design earthquake by using a Finite Elements program in an element of the core. The element

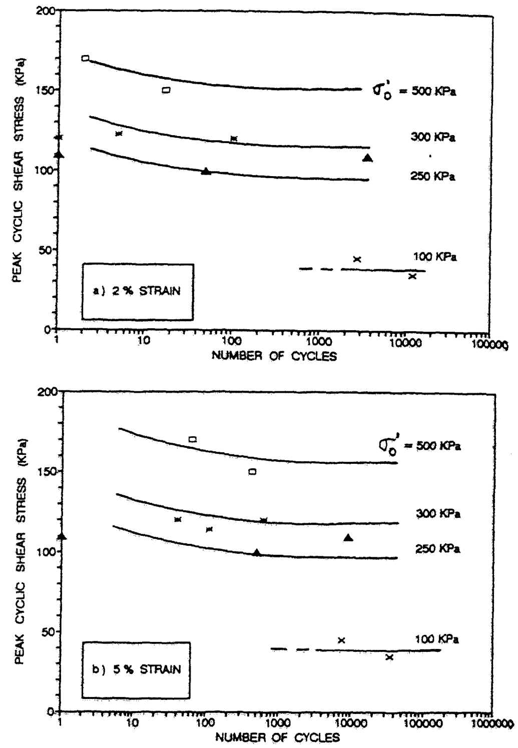

Figure 4. Cyclic stress required to cause peak to peak axial strains in "trimmed" samples

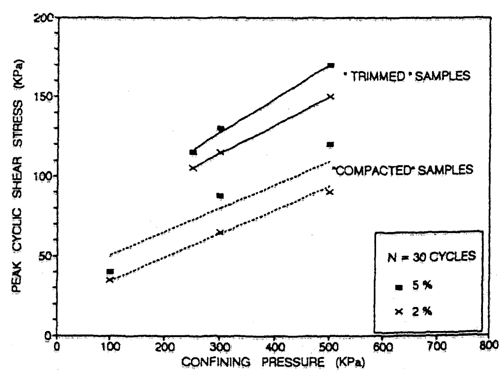

Figure 5. Degradation behaviour of clay

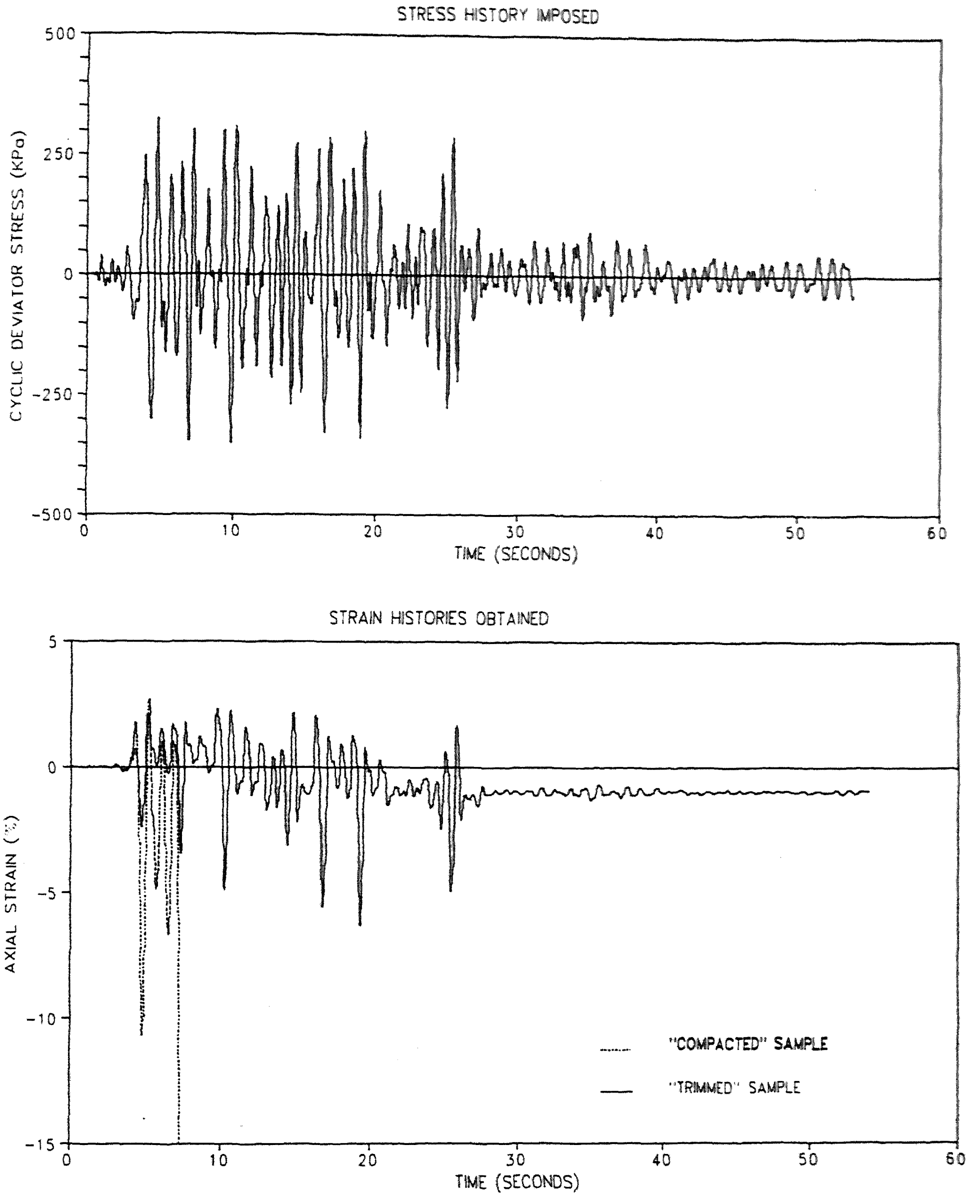

Figure 6. Strain histories obtained in "compacted" and "trimmed" samples under irregular stress history calculated for design earthquake

lies in an area of the core where, according to the criterion given by Makdisi et al. (1978), "potential" strains higher than 5% might be induced by the design earthquake.

Figure 6 shows the strain histories induced in both samples by the irregular history of the load deviator obtained from multiplying by a factor of 2, the shear stress history calculated in that element of the dam for the design earthquake. To introduce this signal into the dynamic triaxial equipment, it was provided with a new PC terminal and the necessary software for communicating with the GA-600 General Automation computer.

One can find several works in the literature dealing with the question of how to reduce the irregular load histories of earthquakes to equivalent histories of uniform cycles, but most of them are only concerned with data relevant to sand deposits: Prakash and Gupta (1970), Lee and Chan (1972), Ishihara and Yasuda (1973), Lee and Focht (1975), Seed et al. (1975), so it is of interest to check how that methodology may also be applied to clay.

Using the procedure recommended by Lee and Chan (1972), the shear stress history given in Figure 6 (with a maximum value of 185 kN/m^2), has been reduced to an equivalent history of 30 cycles of uniform load with an amplitude of 125 kN/m^2. The last significant cycle of the irregular stress history, begins at 25.5 seconds, ends at 26.2 seconds and has an amplitude that is very close to the equivalent load. The peak to peak axial strain obtained with the "trimmed" sample for that cycle, is 4% (see Figure 7), a value which bearing in mind the dry density of the sample, agrees with the one corresponding to (a maximum shear stress of = 125 kN/m^2) in the curve given for "trimmed" samples in Figure 5.

As far as the behaviour of the compacted sample is concerned, it failed after 7 seconds, having undergone peak to peak axial strain greater than 20%; this is not inconsistent with the information provided by Figure 5, for this type of samples, where, for a shear stress amplitude of = 125 kN/m_2, a peak to peak axial strain bigger than 5% is obtained.

6. CONCLUSIONS

From the results obtained in this work, it can be concluded that the final dry density of the material in the core is appreciably different from the value used in design, and that this is a result of the special conditions that existed during the construction of the Canales Dam. As a result, both the elastic shear stress modulus and the cyclic shear resistance of the undisturbed samples retrieved from the borings made in the dam core after construction, are considerably greater than those estimated during the construction stage from the behaviour of samples compacted

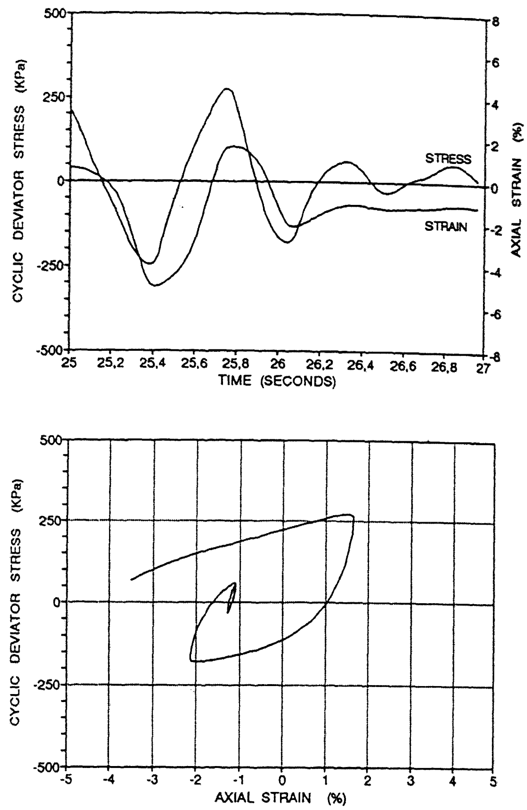

Figure 7. Effect of last significant stress cycle on trimmed sample

in the laboratory to the density specified in the project.

The curves that provide the variation in the modulus ratio G/G_{MAX} and the damping ratio D with the shear strain, do not depend on the confining pressure and agree with data published recently by others.

The fact that the triaxial equipment used makes it possible to accurately reproduce the stress histories calculated for the design earthquake at the dam, has permitted a comparison, for one element of the core, between the strain history obtained with 30 cycles of uniform equivalent load and that caused by the irregular stress history calculated. Preliminary results confirm also for clays the adequacy of the methodology normally used for sands to convert irregular stress histories into equivalent uniform ones.

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