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DYNAMIC BEHAVIOR OF THE SOILS FORMING THE PIEDRAS BLANCAS DAM

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ABSTRACT

This paper presents the results of the dynamic behavior of the metamorphic residual soils that form the embankment and foundation of the Piedras Blancas Dam, owned by the Empresas Públicas de Medellín. This dam was built in the early fifties and it is considered the first high earth dam built in the department of Antioquia, and perhaps one of the first in Colombia. It is located northeast of the city of Medellín (Colombia), in an area of intermediate seismic activity. The purpose of the study was to assess the vulnerability of the dam to damage in the event of a major earthquake, and to design the corrective works, if necessary. This paper also confronts the results obtained for this dam with information obtained from dynamic testing carried out for other dams built in Antioquia, using residual soils from igneous rocks, such as Troneras, Miraflores, Punchiná and Riogrande II dams.

KEYWORDS

Piedras Blancas dam, residual soils, dynamic triaxial tests, metamorphic rocks, igneous rocks, pore pressure.

INTRODUCTION

The Piedras Blancas dam was the first earth dam built in Antioquia and perhaps one of the first in Colombia (Li, 1983). It was designed by Gannett Fleming (USA) and built in 1947-1952 by the a colombian contractor.

Design criteria and construction techniques have evolved since the time where the dam was built, in such a way that the high water content of the soils was not considered an important factor in the original design of the structure. Therefore, during construction it was necessary to substitute the compaction equipment and the soil was unable to reach the maximum densities obtained in the Proctor standard compaction test.

The Piedras Blancas dam showed a normal behavior during the first ten years of operation of the reservoir. However, after 1962 a migration of fine soil particles through the filter was detected, particularly when the water in the reservoir was over certain level. Since that time Empresas Públicas de Medellín has conducted

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some partial studies (Integral S.A., 1963, 1985) looking for solutions to this problem. Besides, the dam has been object of local minor repairs and the reservoir has been operated at the minimum operational level in order to keep a minimum factor of safety.

As part of the program of modernization of old dams undertaken by Empresas Públicas de Medellín, a complete dynamic study was carried out to evaluate the seismic resistant and safety conditions of the dam, and to design the necessary corrective measures. The study took into account the location of the dam in a seismic environment with medium to high activity, and the effect that its eventual failure could cause in the urban area of the neighboring city of Copacabana. This work was carried out by Sedic, a consulting engineering firm from Medellín, with the advisory of Integral S. A.

The study consisted of an extensive investigation of the subsoil conditions with rotary drill borings, deep test pits and seismic cross-hole testing. It also included a comprehensive laboratory investigation including the execution of cyclic triaxial tests to study the pore pressure building under dynamic loading. The tests were carried out at the laboratory of Dr. Killian de Fries in Caracas, Venezuela.

This paper briefly presents the results of the study mentioned above (Integral S.A.-Sedic, 1994), with more emphasis on the dynamic behavior of the soils that constitute the dam embankment and foundation. It also describes the differences observed in the behavior of soils derived from methamorphic rocks in relation to soils derived from igneous rocks, under cyclic loading.

GENERAL DESCRIPTION OF THE PIEDRAS BLANCAS DAM

The Piedras Blancas dam is located northeast of the city of Medellín, at the site where the Chorrillos creek discharges into the Piedras Blancas creek, as indicated in Fig. 1. The dam site is on an important amphibolic metamorphic belt (orthoanphibolite) of igneous origin and Paleozoic age, with a north-south general trend. According to the geomorphology of the zone, this group of rocks exposes different degrees of weathering in their upper levels.

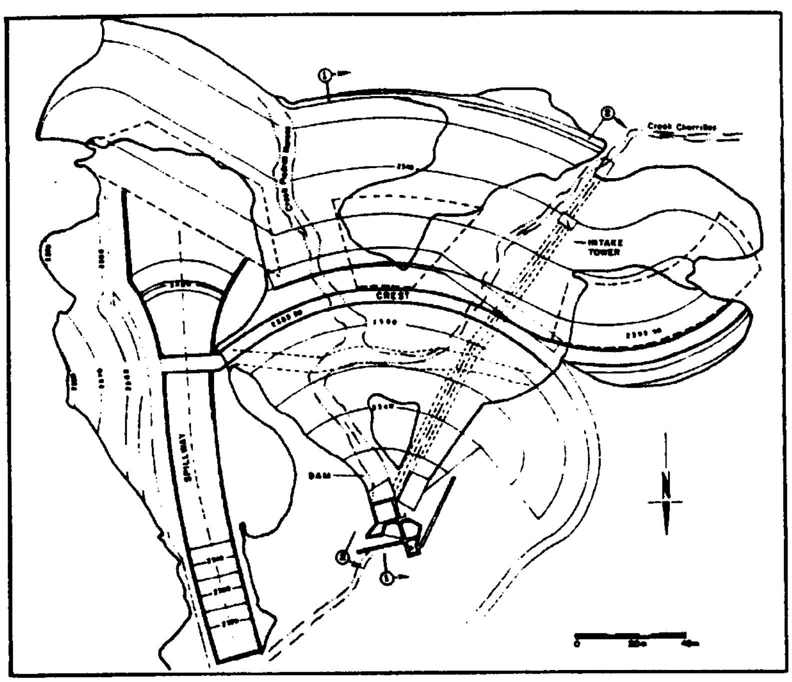

Fig. 1. Plant view

The dam has an homogeneous section and it is confined by two small hills, one of which separates the mentioned creeks. The dam reaches a maximum height of 26 meters and it has a 6 m wide crest at level 2353.5. It was designed with a 3.5 meter freeboard for a reservoir volume of 1.2 million m^3 and water area of 19 Ha. Figure 1 shows a general plan view and Fig. 2 shows typical sections of the dam.

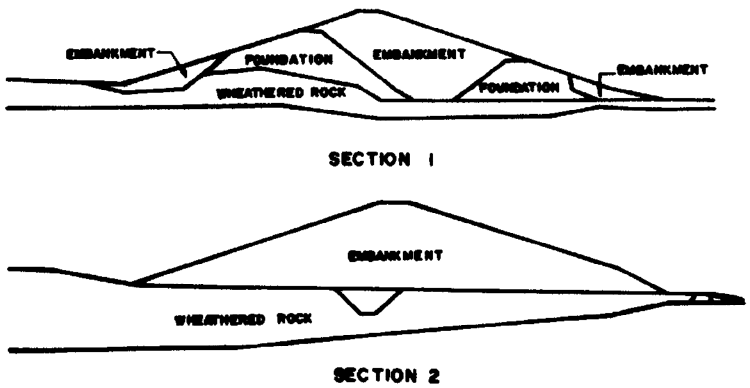

Fig. 2. Typical sections

The dam fill can be described as a medium to high plasticity silt, although most of the soil samples studied were classified as ML in accordance to USCS, and only some of them were reported as MH. Inside the embankment there are also some boulders of considerable size. The soils are the product of weathering of the amphibolite rocks common in the area of the dam and they were obtained from a borrow pit located on the left abutment.

The dam is laid out over amphibolite residual soil with a profile consisting of a 2 meters thick permeable topsoil horizon, followed by a second layer of an impervious plastic clayed silt, which rests on a third layer of weathered amphibolite that keeps textural and structural features from the parental rock. The permeable character of the first layer is the result of dissolution and lixiviation processes that occurred in the weathered amphibolite. As opposed to what happens in soils derived from igneous rocks, there is no a transition zone between the second and third layers. Except over the creek courses, the dam is standing over the second layer, which exhibits a variable thickness between 5 and 20 meters.

SEISMIC CONDITIONS

The Piedras Blancas dam is located in the northwestern part of Colombia and therefore of South America, in a complex sector due to the interaction of three tectonic plates, namely: the South American plate with an easterly-westerly movement, the Nazca plate moving from west to east and subducting under South America, and the Caribbean plate which moves from southwest to northeast.

Within this tectonic framework, the Piedras Blancas dam is located on a metamorphic belt on the west side of an homogeneous tectonic block constituted by the Antioquian Batholite (Batolito Antioqueño) and surrounded by seismic sources of important activity.

The seismic activity at the dam site can be related to two main sources: a deep one associated with the Benioff Zone of the Nazca plate subducting the South American plate, and a shallow one associated with the western Cordillera faults, the Espíritu Santo fault and the Romeral system of faults. The first source has been related to the origin of strong earthquakes in the area of Viejo Caldas. The faults corresponding to the second source have been apparently inactive but they are important due to their proximity to the dam site.

As a result of the seismic hazard study it was established that at the dam site it is expected a peak horizontal acceleration of 0.2 g for a recurrence interval of 500 years.

SOIL PROPERTIES

The study included a detailed subsoil investigation, consisting of nine hand-made pits up to 14 m deep and eight rotary-drill boreholes up to 18 m deep. Cross-hole tests were carried out in the borings by personnel of Empresas Públicas de Medellin, in order to measure the soil wave propagation velocities.

Disturbed and undisturbed samples were taken from the boreholes for classification and characterization of the materials under static conditions. Undisturbed block samples were taken from the pits and submitted to the laboratory for the execution of 23 cyclic triaxial tests under controlled stress conditions. The tests were intended to quantify the buildup of pore water pressure and the accumulated deformation, under cyclic loading.

Index and static soil properties

The results of the classification tests indicated that the soils that constitute the dam are clayey silts mostly corresponding to the group ML, although there were some samples in the group MH. The average liquid and plastic limits obtained for these soils are 47.3% and 34.9% respectively, and the percentages per weight of the soil constituents are 19% of sand, 63% of silt and 18% of clay and colloids. The average natural water content is greater than 40%, which is several points above the optimum water content defined with the Proctor standard compaction test. In general the soils exhibit a degree of saturation close to 100% and this condition prevails even for those materials located near the filter.

Table 1 contains the results of the static triaxial tests executed with soil samples from the embankment and foundation. The strength tests indicated that the soils have a high shear resistance, despite their relatively high water contents. All the materials, including the compacted soils of the embankment, showed a behavior characteristic of overconsolidated soils, probably due to a soil aging phenomena.

Table 1. Summary of static triaxial tests results

Material	Test	Density (t/m^3)		Effect. stress		Total stress	
		Moist	Sat.	C'(t/m^2)	ø'	C(t/m^2)	ø
Embankment	CD	1.91	1.91	4.1	34		
	CU			3.5	36	3.3	27
Foundations	CD	1.59	1.72	3.7	30		
	CU			2.2	32	3.6	21

Dynamic soil properties

Shear wave velocities ranging from 160 to 320 m/sec were defined with the cross-hole tests. The compression wave velocities obtained with these tests were not considered representative of the dynamic soil behavior due to the conditions of saturation of the materials.

The maximum shear modulus was defined from the shear wave velocities obtained with the geophysical tests, and from empirical correlations with the Standard Penetration Resistance. This modulus represents the elastic behavior of the soil for very small strains (smaller than $1*10^{-4}$ %). Figure 3 shows the shear modulus values as a function of the confining stress. The maximum shear modulus can also be expressed as:

$$G_{max} = 1000 * K_2 * (\sigma_o)^{1/2} \qquad \text{(p.s.f.)} \qquad (1)$$

Where: K_2 : Nondimensional parameter
σ_o : Mean effective stress

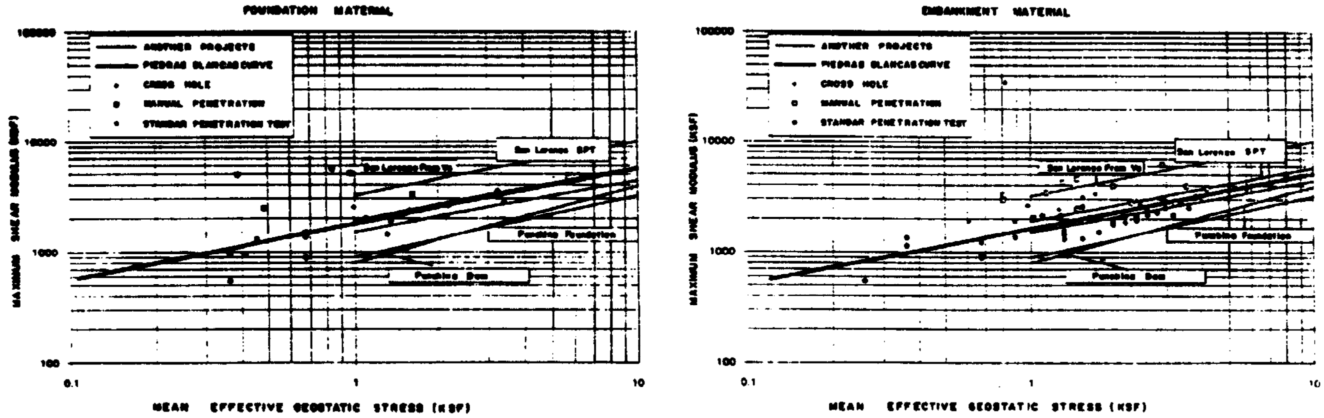

Fig. 3. Shear modulus vs. confining stress

Interpolation of the results presented in Fig. 3 according to the stress levels, yielded values of the K_2 parameter of 55 and 50 for the embankment and foundation materials, respectively. These values show good agreement with those reported in the related literature.

Figure 4 shows the variation of the ratio between the shear modulus and the maximum shear modulus with the shear strain level, for the embankment and foundation soils. These curves were constructed from the analysis of the hysteretic cycles defined with the tests performed. However, it is important to point out that the tests were of the stress controlled type, which are not the most suitable for these kind of evaluation. The results also showed that damping values are rather scattered whereas the variation of the modulus is more continuous. The foundation material shows a larger resistance to deformations and a lesser susceptibility to undergo degradation under cyclic loading. When these results are compared with the curves proposed by Vucetic and Dobry (1991) for different plasticity materials, it is observed that they fit a curve corresponding to a greater plasticity index than that measured for the foundation soils, whereas there is a good agreement for the embankment soils.

Figure 5 shows curves for different stress levels, representing the variation with the cyclic stress ratio ($\sigma_d/2\sigma_3$), of the number of cycles under which the soil reaches a peak pore water pressure.

COMPARISON WITH OTHER RESIDUAL SOILS

A comparison of the characteristics of the Piedras Blancas soil (residual from metamorphic rocks) with those of other dams in Antioquia built with residual soils derived from igneous rocks, indicates that there are clear differences between them. The Piedras Blancas soil has a content of fine particles (passing 200 sieve) close to 80%, whereas in the other soils this parameter is around 50%. In addition, the plasticity index and the natural water content of the Piedras Blancas soil are slightly greater than the corresponding values for the other soils considered in this study.

Figure 5 shows curves representing the number of cycles required for the soil to reach a peak pore water pressure as a function of the cyclic stress ratio ($\sigma_d/2\sigma_3$), for both the Piedras Blancas residual soil (metamorphic parental rocks) and residual soils from other Antioquian dams (igneous parental rocks)

(Villegas et al, 1987). It is observed that for the same number of cycles, the Piedras Blancas soil requires a larger cyclic stress ratio for the soil to reach peak pore water pressure than that required for the soils derived from igneous rocks. Figure 6 shows the variation of the dynamic pore water pressure ratio (r_{ud}) with the confinement level represented by the effective vertical stress. The dynamic pore pressure ratio is defined as the relation between the induced pore pressure and the effective vertical stress. It is observed that the peak values of r_{ud} for the Piedras Blancas soil are lower than those obtained for the Batholith soils. Figure 7 shows the variation of the pore water pressure ratio against the number of loading cycles, normalized by their corresponding maximum values. The pore pressure building rate is larger for the soils derived from igneous rocks than for the Piedras Blancas soils, as indicated by a steeper slope of the curve in Fig. 7.

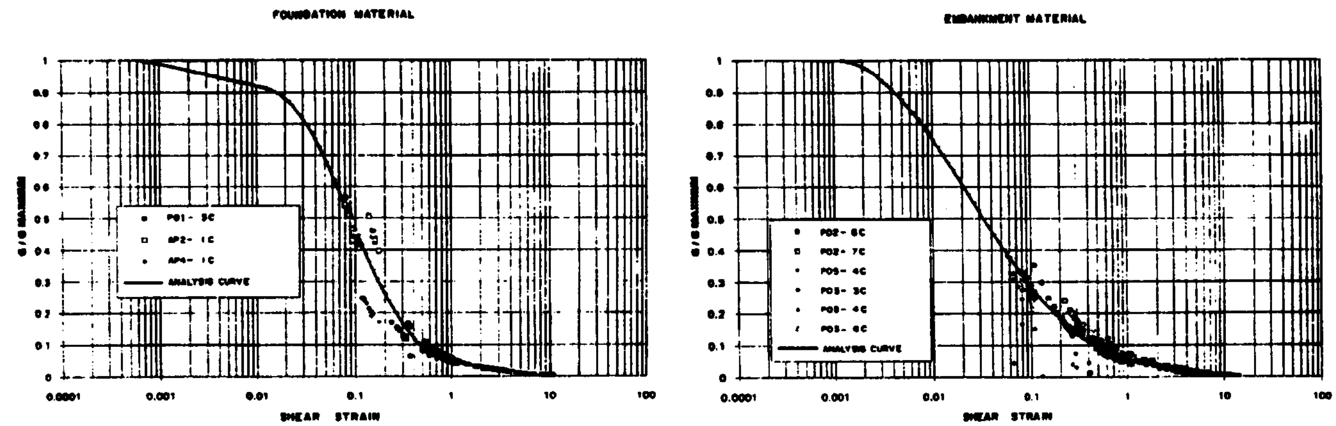

Fig. 4. Shear modulus ratio vs. shear strain level

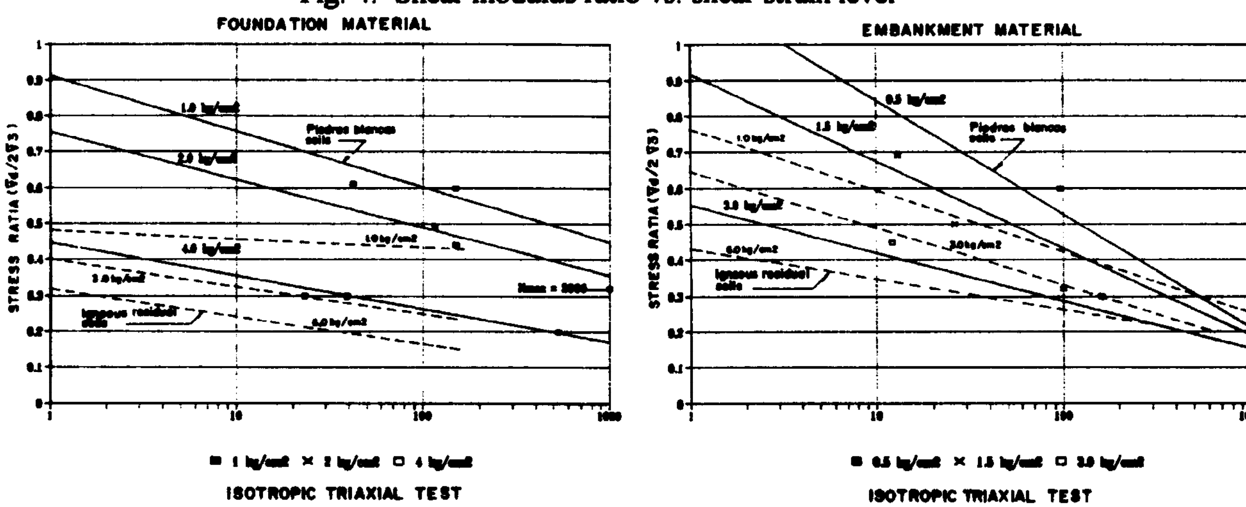

Fig. 5. Cyclic stress ratio vs. Number of cycles

Finally, the Piedras Blancas soil shows smaller induced deformations than those reported for Batholith soils. The peak to peak deformations (e_{pp}) obtained for the Piedras Blancas soil were never greater than 10% in the isotropic cyclic tests. Figure 8 shows the required shear stress to produce in 15 cycles of loading, a peak to peak deformation (e_{pp}) of 10% for the batholith soils and 5% for the Piedras Blancas soils. These curves indicates that even for small deformations the soils derived from metamorphic rocks have greater resistance than those from the batholit.

DYNAMIC ANALYSIS OF THE PIEDRAS BLANCAS DAM

An evaluation of the static and dynamic induced stresses was performed, taking into account the results of the laboratory tests carried out. Several analysis were performed with various two-dimensional finite element programs in order to study the behavior of the dam under static and dynamic conditions. The non-linear behavior of materials was considered in the analysis as well as the construction process.

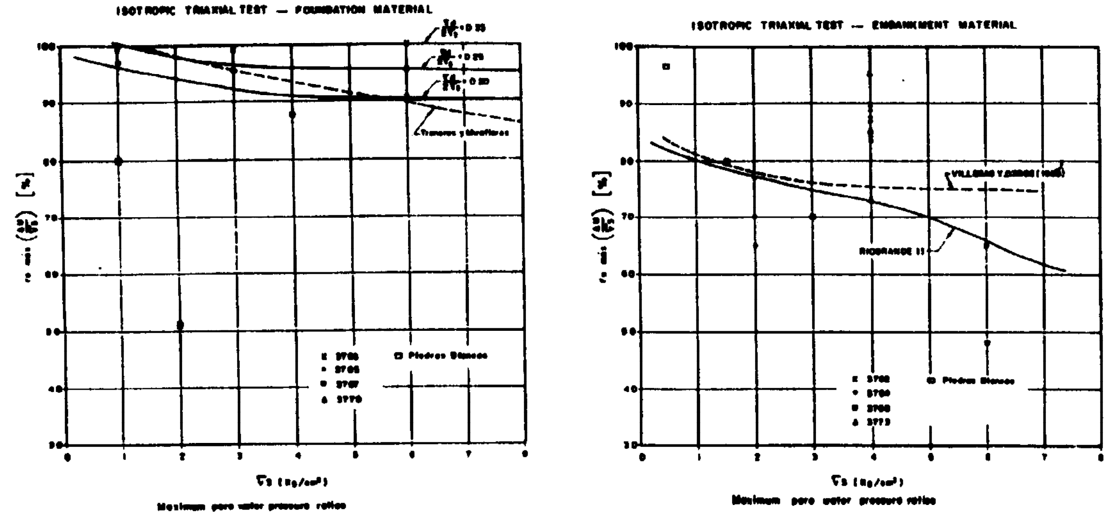

Fig. 6. Variation of the maximum pore water pressure ratio

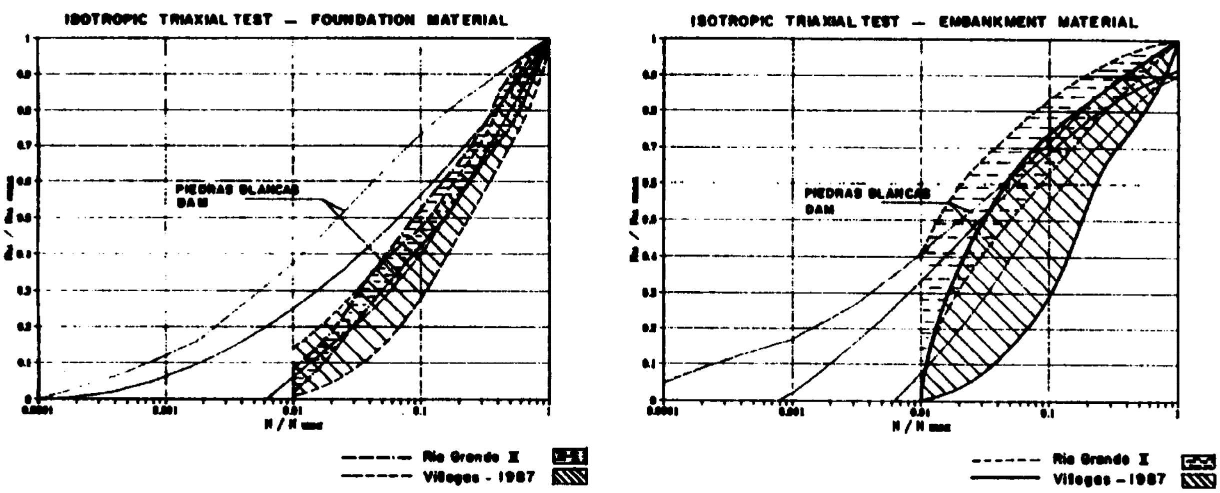

Fig. 7. Water pore pressure ratio vs. Number of cycles

The results of the analysis were used for the calculation of the dynamic pore water pressures in the embankment and its foundation, and these values were used in the stability evaluation of the dam for the post-seismic condition, considered the most critical. Based on these analyses, the conclusion was that the dam would be safe during a seismic event with a recurrence interval of 500 years.

CONCLUSIONS

During an evaluation of the dynamic and static properties of tropical soils, it is necessary to take into account the origin of the rocks from which these soils are derived.

The soils constituting the embankment and foundation of the Piedras Blancas dam are more resistant under dynamic loading than those used in other dams in Antioquia. This behavior is attributed to the metamorphic origin of the parental rock, the greater content of fine particles and the greater plasticity indexes.

The Piedras Blancas dam is safe for seismic events with a recurrence of 500 years, due to the static and dynamic properties of the soils forming the embankment and its foundation.

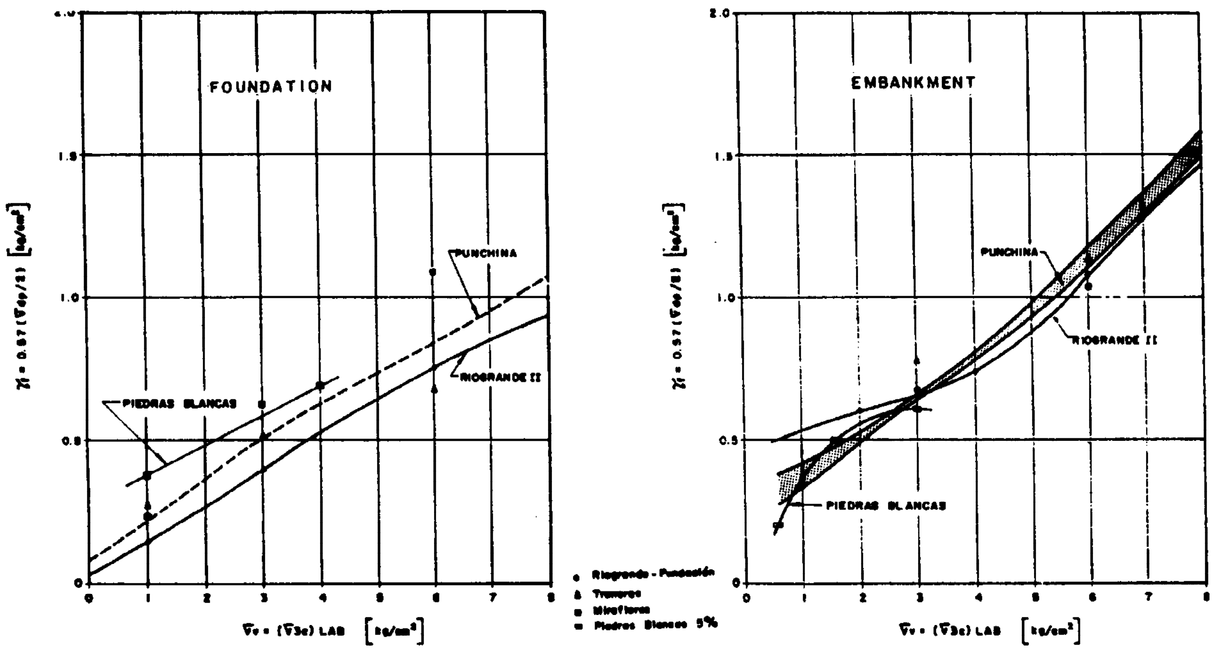

Fig. 8. Shear stresses for ε_{pp}

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