STUDY OF AN ORTHOTROPIC ROCK MASS: EXPERIMENTAL TECHNIQUES, COMPARATIVE ANALYSIS OF RESULTS

Étude d'un massif rocheux orthotrope. Techniques expérimentales, analyse comparative des résultats

Untersuchungen an einem orthotropen Gebirge. Versuchstechniken, vergleichende Analyse der Ergebnisse

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SUMMARY

This paper illustrates "in situ" static and geophysical investigations carried out on an orthotropic rock mass consisting of alternating sandstone and marl, for the design of an arch-gravity dam.

A method of interpretation of the results of plate bearing test in a direction normal to the stratification, is developed being based on the measure of the deformations at different depths from the rock surface.

Sonic logs and cross-hole measures are also examined and the results are correlated with those obtained by static loading tests.

RESUME

Le rapport décrit les prospections statiques et géophysiques effectuées "in situ" sur une roche orthotropique composée alternativement de grès et de marne, en vue d' un projet pour un barrage poids-voûte.

Pour interpréter les résultats des essais de charge sur plaque dans la direction normale de la stratification, on a développé une méthode basée sur les mesures des déformations à différentes profondeurs de la surface de la roche.

En outre, on a examiné les mesures géophysiques et les résultats ont été mis en corrélation avec ceux obtenus par les essais sous charge statique.

ZUSAMMENFASSUNG

Der Bericht beschreibt statische und geophysikalische Untersuchungen, die für den Entwurf einer Bogengewichtsmauer, an Ort und Stelle, an einer abwechselnd aus Sandstein und Mergel bestehenden, orthotropischen Felsmasse vorgenommen wurde.

Zur Auslegung der Ergebnisse der Plattendruckversuchen in normaler Richtung der Schichtung wurde eine Methode entwickelt, die die Messungen der Deformationen an verschiedenen Tiefen aus der Felsoberfläche auswert.

Auch wurden geophysikalische Messungen untersucht und mit den Ergebnissen der Statischen Versuchen korreliert.

1. FOREWORD

This paper presents the results of investigations carried out by different techniques on the foundation rock of an arch-gravity dam in the Central Apennines.

The rock mass concerned consists of a rhytmically alternating sandstone and marl, its bedding plane striking N 52 W - dip 27°. Each separate sandstone-marl sequence has variable thickness, from a few decimeters to over 7 m, with an extended continuity of the bedding planes.

From the litho-stratigrafic point of view, the rock mass is characterized by marked orthotropy. For this very reason an interpretative study of measurements taken during the "in situ" investigations has been deemed significant.

These investigations have been carried out according to different techniques, that is:

1. "in situ" deformability tests (plate bearing tests in a section of a tunnel with axis parallel to the plane of stratification);
2. geophysical investigations in the area involved by deformability tests.

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To understand the symbols used in this paper, we recall the stress-strain relationship in elastic anisotropic continua (where orientation of the axes appears to be as in Fig. 1):

$$\varepsilon_x = \frac{\sigma_x}{E_1} - \frac{\nu_2}{E_2}\sigma_y - \frac{\nu_1}{E_1}\sigma_z$$

$$\varepsilon_y = -\frac{\nu_2}{E_2}\sigma_x + \frac{\sigma_y}{E_2} - \frac{\nu_2}{E_2}\sigma_z$$

$$\varepsilon_z = -\frac{\nu_1}{E_1}\sigma_x - \frac{\nu_2}{E_2}\sigma_y + \frac{\sigma_z}{E_1}$$

$$\gamma_{xz} = \frac{2(1+\nu_1)}{E_1}\tau_{xz}$$

$$\gamma_{xy} = \frac{\tau_{xy}}{G_2} \qquad \gamma_{yz} = \frac{\tau_{yz}}{G_2}$$

in shortened form $|\varepsilon| = |K| \cdot |\sigma|$ (1)

Further on we shall be introducing the following ratios:

$$n = \frac{E_1}{E_2} \qquad m = \frac{G_2}{E_2}$$

and we shall be considering $\nu_2 = 0$, in order to simplify calculations.

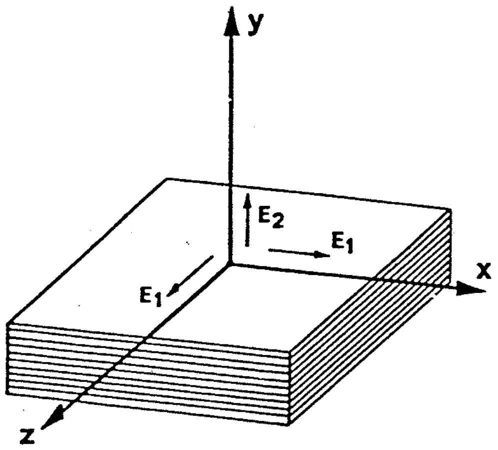

FIG. 1 Orthotropic medium: reference axes.

2. IN SITU GEOMECHANICAL INVESTIGATIONS

To determine the deformability characteristics of the rock mass an exploratory tunnel was excavated, its axis being parallel to the bedding plane.

Plate bearing tests were carried out in a direction either normal or parallel to the bedding planes, using the testing technique widely experimented by ISMES. This technique allows the deformation measurement inside the rock mass, into a borehole drilled at the center of the bearing plate, by means of special borehole extensometer provided with mechanical expansion anchors.

Thus a remarkable advantage is obtained, that is to determine deformability characteristics of the undisturbed rock mass below the "loose" zone alterned by the excavation of the exploratory tunnel.

This substantial progress in measuring instruments is associated with an improvement in the load application technique . It is therefore possible to achieve, with fair approximation, the theoretical uniformely-distributed load scheme, by using deformable jacks directly applied against rock surface.

Diagrams of settlements as a function of the depth for different values of the pressure applied to the rock (2, 4, 6 MN/m^2) are shown in Fig. 2. The results are relative to tests carried out with a 60 cm- diam. plate in a direction normal and parallel to the stratification. It can be observed that the deformation process reaches a depth of 6 times the diameter of the loading plate.

Deformability measurements in tunnel, in a direction perpendicular to the layers, have been interpreted by a formula which may be strictly applied to an orthotropic halfspace loaded with uniform pressure on a circular surface, where settlement measures are performed on surface and at various depths, at the loading axis.

A previous paper [4] reported the result of a calculation showing that the settlements measured at various depths in the orthotropic halfspace are function, essentially, of the normal elastic modulus E_2 (referring to the direction perpendicular to layers) and tangential elastic modulus G_2 (referring to a plane containing the normal to stratification). The normal modulus E_1 (relevant to the bedding plane) has scarcely any effect on these settlements; Poisson' s ratios ν_1 and ν_2 (hereinafter ν_2 is assumed, for simplicity, to be equal to 0) have only a slight influence and therefore they are of negligible extent.

Considering therefore the functional link existing between the different parameters, the measurement of settlements at two different depths can make possible the formulation of a system of two equations in the two unknown quantities E_2 and G_2.

Without going into the treatment, for which the reader is referred to the aforementioned paper, the following expression is obtained as regards the settlement at depth y from the plane deliminting the indefinite halfspace (where p is the uniform pressure applied on a circular surface of radius r):

$$v = \frac{\sqrt{n}\,p}{\sqrt{1-\nu_1^2}\,E_2(s_1-s_2)} \cdot \left\{ \frac{1}{s_1^2}\left[\sqrt{r^2+s_1^2y^2} - s_1 y\right] - \frac{1}{s_2^2}\left[\sqrt{r^2+s_2^2y^2} - s_2 y\right] \right\}$$

where

$$s_1 = \sqrt{\frac{\frac{n}{m} + \sqrt{\left(\frac{n}{m}\right)^2 - 4n(1-\nu_1^2)}}{2(1-\nu_1^2)}}$$

$$s_2 = \sqrt{\frac{\frac{n}{m} - \sqrt{\left(\frac{n}{m}\right)^2 - 4n(1-\nu_1^2)}}{2(1-\nu_1^2)}}$$

$$n = E_1/E_2 \qquad m = G_2/E_2$$

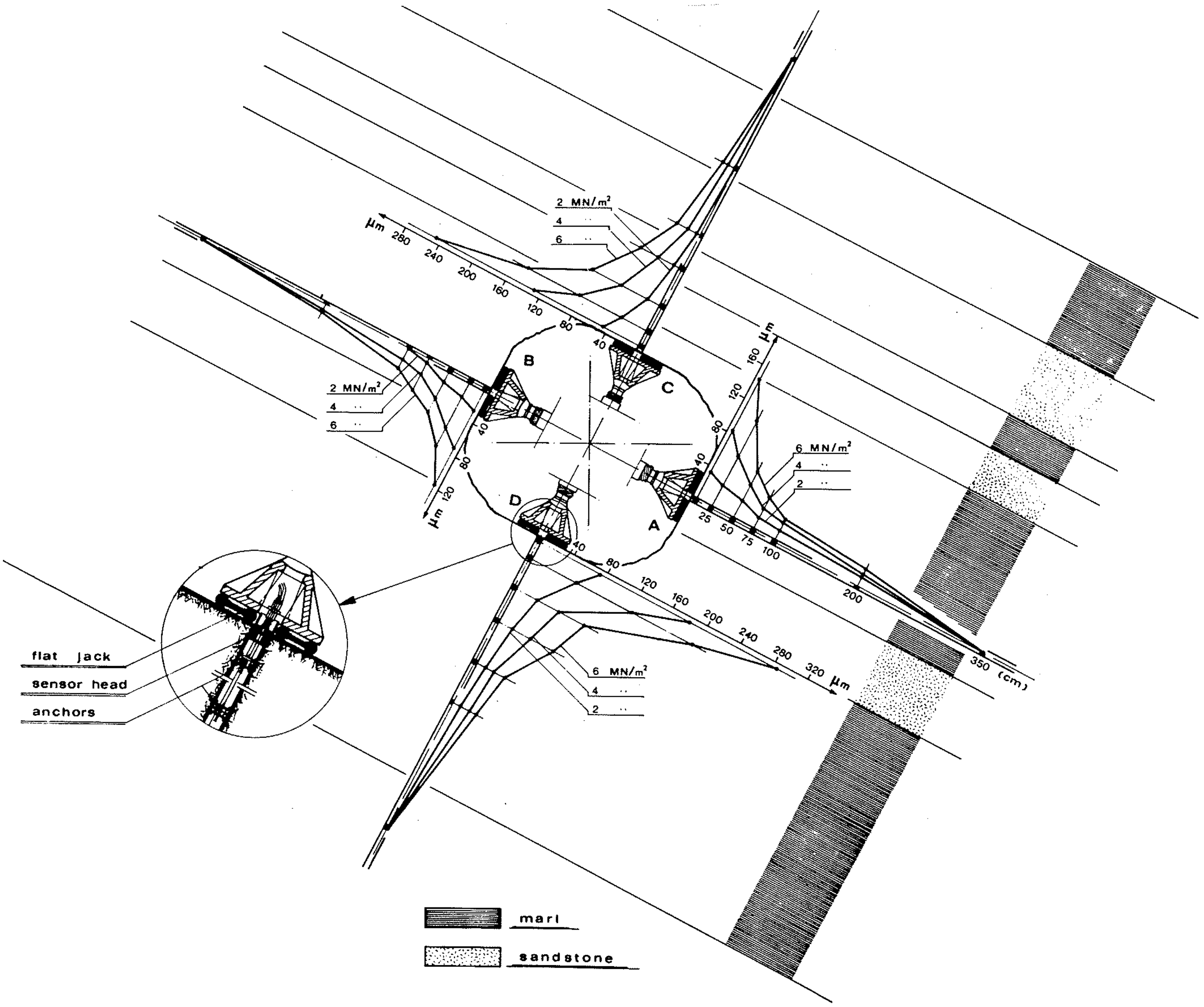

FIG. 2 Diagram of settlements (along the loading axis), versus depth in a direction normal and parallel to the stratification.

At y = 0, that is on surface, it is:

$$(v_y)_{y=0} = \frac{p\,r\sqrt{n}}{E_2} \cdot \frac{s_1 + s_2}{(s_1 \cdot s_2)^2}$$

and generically we may write:

$$v_y = v_0\,\frac{s_2^2\left[\sqrt{1+s_1^2\left(\frac{y}{r}\right)^2} - s_1\frac{y}{r}\right] - s_1^2\left[\sqrt{1-s_2^2\left(\frac{y}{r}\right)^2} - s_2\frac{y}{r}\right]}{s_2^2 - s_1^2}$$

Table 1 shows, for a wide range of n and m values, the values of v_o/v_y ratios, being v_r the settlement for y = r, and v_{2r} for y = 2 r, etc. The values of v_y/v_o are reported in the diagrams of Fig. 3.

The aforementioned formulae were used to interpret the deformometric readings taken during the rock tests discussed in this paper and shown in Table 2.

Deformations were measured on the principle of obtaining, in subsequent processings, the secant moduli of elasticity.

Settlements v_r and v_{3r}, that is for y = r and

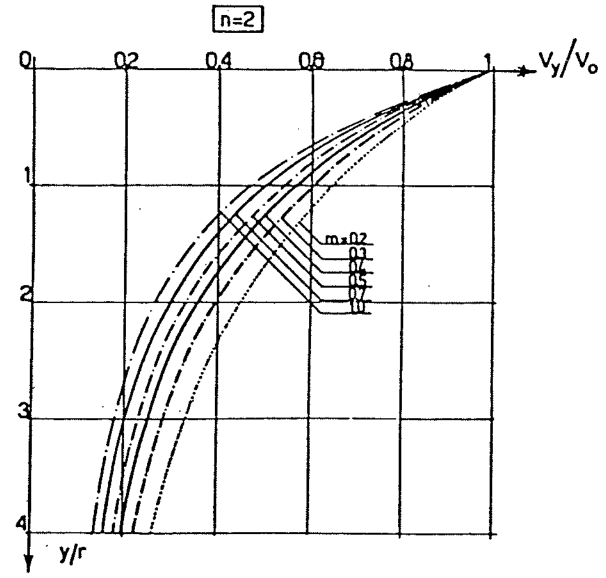

FIG. 3 v_y/v_o versus depth for different m-values and for n = 2.

TABLE 1

n	m	v_0/v_r	v_0/v_{2r}	v_0/v_{3r}	v_0/v_{4r}	$\frac{(s_1+s_2)\sqrt{n}}{(s_1 \cdot s_2)^2}$
1	0.2	1.5106	2.1938	2.9632	3.6777	2.6464
	0.3	1.6252	2.4891	3.4537	4.4615	2.3098
	0.5	1.7828	2.9253	4.1786	5.4556	2.0000
	0.7	1.89486	3.24354	4.70419	6.19785	1.8516
	1.0	2.01124	3.58613	5.27361	6.98485	1.730
2	0.2	1.5245	2.2178	2.9864	3.8044	2.5332
	0.3	1.6498	2.5275	3.5093	4.5207	2.1792
	0.4	1.7522	2.7893	3.9288	5.1099	1.9798
	0.5	1.8389	3.0136	4.2929	5.6115	1.8481
	0.7	1.9793	3.3825	4.8902	6.4320	1.6863
	0.8	2.03739	3.53754	5.14172	6.77851	1.6322
	1.0	2.13598	3.80212	5.56956	7.36456	1.5537
3	0.2	1.5298	2.2198	2.9949	3.8147	2.4816
	0.3	1.6604	2.5424	3.5207	4.5436	2.1192
	0.5	1.8630	3.0496	4.4397	5.6699	1.7765
	0.7	2.0185	3.4430	4.9715	6.5345	1.6073
	0.8	2.08387	3.61104	5.24025	6.91204	1.5507
	1.0	2.19708	3.9023	5.70649	7.53926	1.4678
4	0.2	1.5326	2.2255	2.9993	3.8201	2.4504
	0.3	1.6664	2.5504	3.5311	4.5559	2.0820
	0.5	1.8768	3.0694	4.3658	5.7025	1.7323
	0.7	2.0411	3.4777	5.0177	6.5932	1.5585
	0.8	2.11161	3.6534	5.2977	6.97581	1.5000
	0.9	2.17555	3.8142	5.55314	7.32385	1.4529
	1.0	2.2542	3.9601	5.7850	7.6394	1.4142

y = 3r respectively, have been analysed to the purpose of excluding surface measurements (v_0), clearly influenced by the excavation of the tunnel.

The choice of v_r and v_{3r} is connected with the double requirement to have at disposal rather reliable readings (v_{4r} for instance is difficult to estimate, and therefore susceptible of remarkable measurement errors) and rather diverging (v_r is clearly higher than v_{3r}), in order to obtain the maximum sensitivity in the following procedure. The values of the ratio v_r / v_{3r} are reported in Table 2 which is constructed from the data in Table 1. The substantial non-influence of the ratio v_r/v_{3r} from the values of n can be observed.

TABLE 2

n	m	v_r/v_{3r}	n	m	v_r/v_{3r}
1	0.2	1.9616	3	0.2	1.9577
	0.3	2.1277		0.3	2.1204
	0.5	2.3438		0.5	2.3831
	0.7	2.4827		0.7	2.4631
	1.0	2.6221		0.8	2.5147
2	0.2	1.9589		1.0	2.5873
	0.3	2.1229	4	0.2	1.9570
	0.4	2.2422		0.3	2.1190
	0.5	2.3345		0.5	2.3262
	0.7	2.4707		0.7	2.4583
	0.8	2.5238		0.8	2.5088
	1.0	2.6076		1.0	2.5893

As an example we shall process the data referring to plate C of Fig. 2. For a load $\Delta p = 2$ MN/m^2 we obtain: $v_r/v_{3r} = 2.5$, wherefore from Table follows $m \simeq 0.75$ (at $n = 2$, mean value); however, from Table 1 we obtain at $m \simeq 0.75$ (through interpolation) values of v_0/v_r that vary from 1.91 (for $n = 1$) to 2.07 (for $n = 4$).

Confirmed the slight influence of n, we have assumed for v_0/v_r an average value equal to 2.008, still corresponding to $n = 2$; it then follows:

$$v_r = \frac{v_0}{2.008} = \frac{p\, r \sqrt{n}\,(s_1 + s_2)}{2.008 \cdot (s_1 \cdot s_2)^2 \cdot E_2} = 30 \cdot 10^{-3}\ \text{cm}$$

from which:

$E_2 = 16,520$ MN/m^2

$G_2 = m\, E_2 = 12,390$ MN/m^2

Similar processings for the other pressure levels give:

for $\Delta p = 4$ MN/m^2 $E_2 = 14,420$ MN/m^2
$G_2 = 8,600$ MN/m^2

for $\Delta p = 6$ MN/m^2 $E_2 = 12,435$ MN/m^2
$G_2 = 7,400$ MN/m^2

Considering the criterion assumed in selecting the experimental results, in relation to the progressive development of inelastic phenomena, which, in this interpolation are interpreted elastically, through the secant moduli of elasticity, the decrease that occurs in the modulus with the increase in the pressure level appears obvious.

The above procedure is an improvement of usual methods which interpret the mass as isotropic, obtaining the consequent single modulus of elasticity E.

In particular, the use of Boussinesq formula [1] (applicable to the surface or to predetermined depths) and its comparison with experimental data, would make it possible to identify the following modulus of elasticity, that may be evaluated by interpreting deformations measured at depth r = 30 cm.

Δp (MN/m^2)	2	4	6
E (MN/m^2)	20,890	16,200	14,000

In the interpretation according to the anisotropic assumption, E_1 value is not defined; this latter value is practically non-influent on the deformation process analysed.

An indication in the value of E_1 in relation to E_2 may be deduced from the ratio between the deformations measured at the same depth in two plate bearing tests performed in a direction perpendicular and paralleled to the stratification.

3. GEOPHYSICAL INVESTIGATIONS IN THE AREA INVOLVED BY EXCAVATION

A first set of geophysical investigations was carried out on the rock surrounding the exploratory tunnel for an overall thickness of about 30 to 35 m.

Starting from the surface, the vertical holes A_1, A_2 and A_3 were drilled, parallel and equidistant from each other (3 m), intersecting the axis of the exploratory tunnel (Fig. 4).

Sonic logging was carried out in these holes by means of an 1 m-long probe, as well as "cross - hole" measurements every 0. 25 m of depth in a direction parallel to the stratification.

These measurements made it possible to determine the value of the ratio between the velocity of elastic wave propagation in a direction normal and parallel to the stratification. The mean velocity in a direction normal to the stratification, evaluated through the measurements of sonic logs, was v_2 = 4. 3 Km/s and the mean velocity in a direction parallel to layers, furnished by cross-hole measurements, was v_1 = 5 Km/s.

Ratio v_1^2 / v_2^2, which, as is known, coincides with the ratio between the dynamic moduli, is equal to 1. 35.

The determination of this ratio through geophysical measurements, is an useful instrument to evaluate the modulus of elasticity E_1 in a direction parallel to stratification, if the value of E_2, calculated by the method described abode, is known.

Investigation was conducted before and after the excavation of the exploratory tunnel and made it possible, among other things, to appraise the disturbance caused by tunnel excavation in the surrounding mass.

This investigation showed a marked alteration of the marl layer located at the lower part of exploratory tunnel. This appears to be in good agreement with the marked deformation measured during the test performed at plate D.

A second geophysical investigation was performed inside the exploratory tunnel at the 4 holes used for the plate bearing test, in order to compare the data obtained from static loading tests.

Measurements of longitudinal elastic wave propagation velocity were performed on the same bases used for deformation measurements during the plate bearing tests.

These values are compared in Fig. 5 with the deformability moduli values calculated on the assumption of homogeneous and isotropic halfspace, using reversible deformations. The comparison was made in respect both of points on the surface and located at a depth of 50 cm from the rock surface; that is, in a comparatively undisturbed area of the rock mass.

The comparison, which includes results of tests performed in a direction both normal and parallel to the stratification, has to be considered, on the whole, quite significant. It may be noted that the alteration in the rock layer around the exploratory tunnel has a more marked effect on the deformability modulus than on the elastic wave propagation velocity measurements.

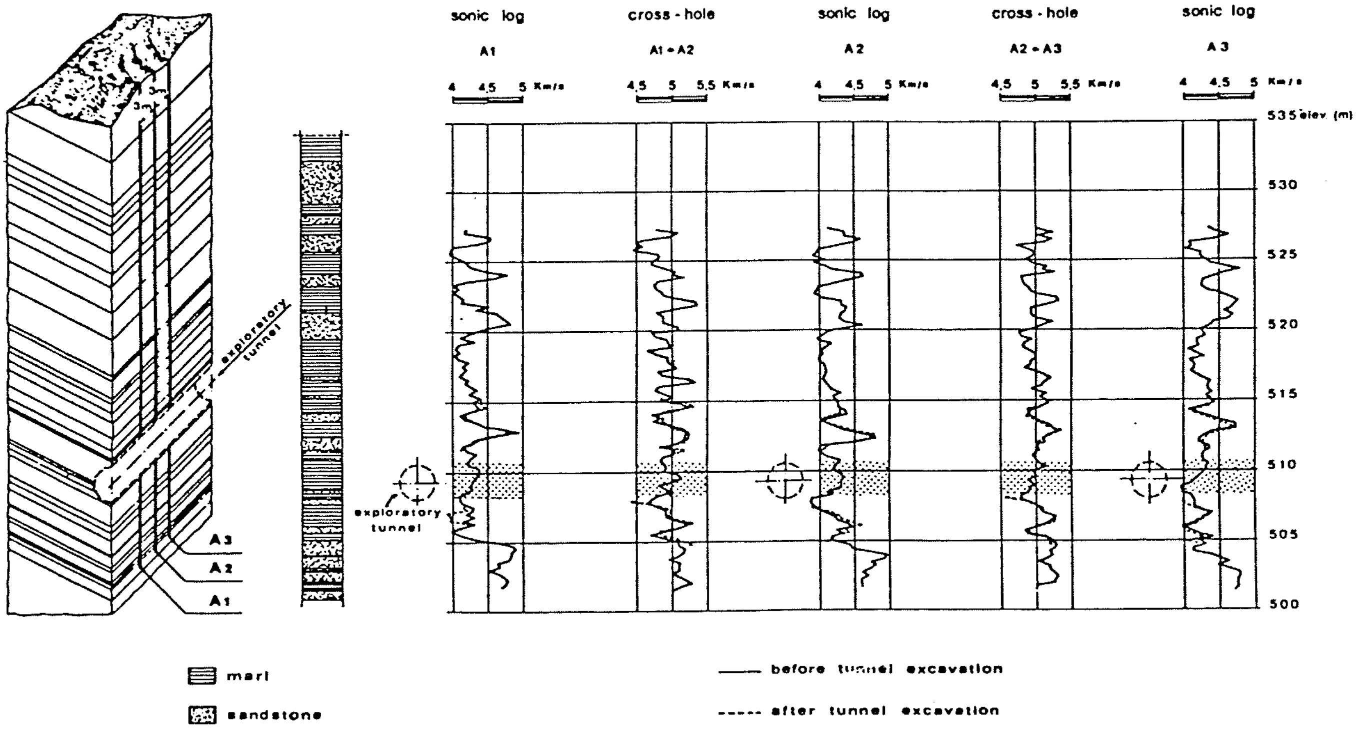

FIG. 4 Sonic logs and cross-hole measures in the rock surrounding the exploratory tunnel.

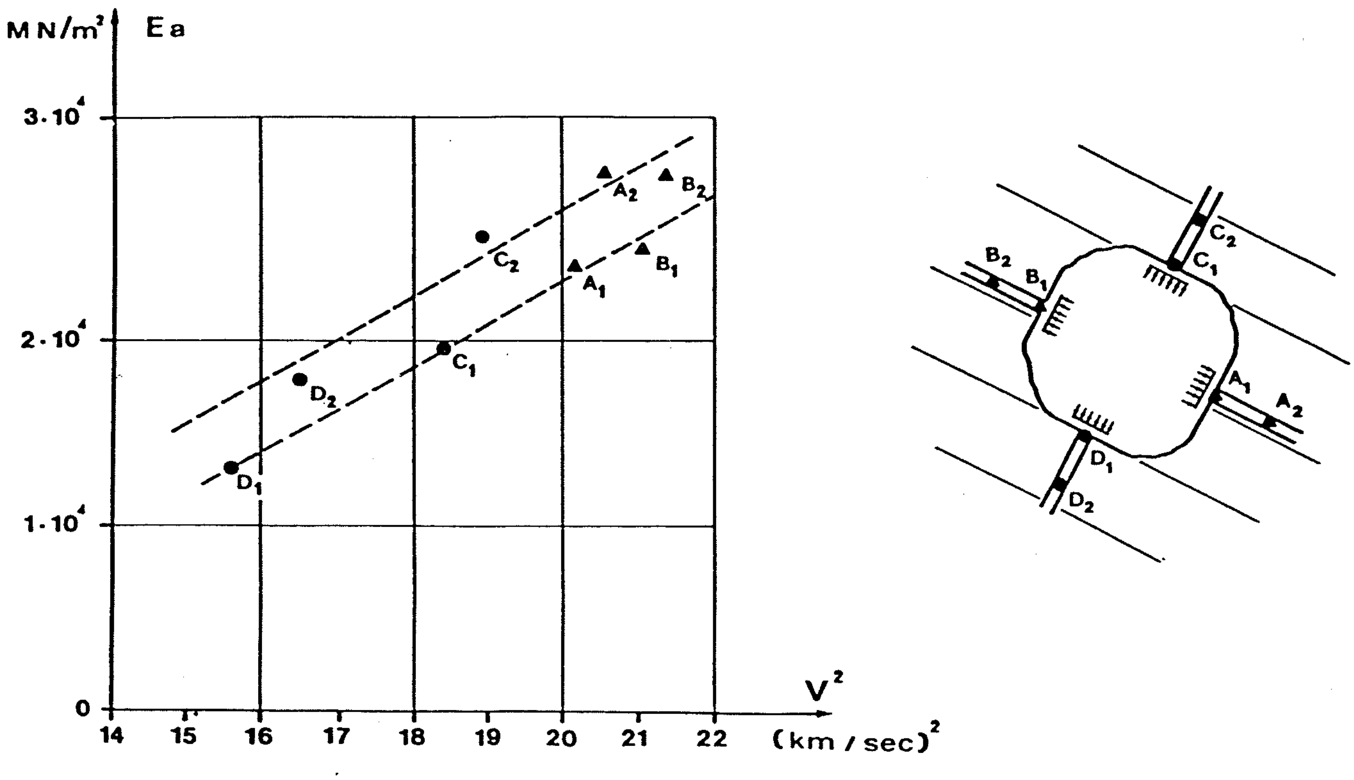

FIG. 5 Correlation between the deformation moduli and the squares of the velocities of elastic waves.

4. FINAL REMARKS

What stated above, is a first report of a test program being still performed, of which complete data are not yet available.

This justifies the not fully exhaustive conclusions, at which we can by now arrive.

Obviously, only a wider harvest of experimental results could make possible more probatory conclusions, if a statistical analysis of acquired information is performed. Such an analysis is, in our opinion, necessary, considering the particular type of rock mass being investigated and the remarkable variability of its characteristics.

Anyhow, it has been considered interesting to emphasized the criterion of the experimental investigation program, and the usefulness of a close connection between static load tests and geophysical measurements. It is to be noted that experimental techniques used have been improved to such an extent as to provide quite reliable results, and this is an essential premise to carry out a correct interpretation of experimental results.

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