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In situ flat jack tests: analysis of results and critical assessment

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IN SITU FLAT JACK TESTS: ANALYSIS OF RESULTS AND CRITICAL ASSESSMENT.

ESSAI AU VERIN PLAT *IN SITU:* ANALYSE DES RESULTATS ET EVALUATION CRITIQUE.

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Summary

This paper presents the results of *in situ* flat-jack tests, i.e. the state of stress and deformability parameters of the rocks recorded during geomechanical investigations to be used for the best design and construction of five large underground pumped-storage power-houses and for the study of the foundation rock of an arch-gravity dam. The great amount of data available was also used for a review of the flat-jack results which were furthermore compared with the original stress measurements (CSIR doorstopper method) and with the plate-loading tests. A different data processing approach for determining the deformability on the basis of the results obtained from an FE tridimensional model is also presented. The abovementioned analyses provide evidence for emphasizing the accuracy and validity of in situ flat-jack measurements.

Résumé

Le rapport donne les résultats des essais au vérin plat *in situ*, c'est-à-dire l'état de contrainte et les paramètres de déformabilité des roches, relevés pendant des recherches géomécaniques visant à améliorer le projet et la sécurité de la construction de cinq grandes centrales en caverne pour le transfert d'énergie par pompage et des fondations d'un barrage poids-voûte. Afin d'obtenir en outre la meilleure utilisation des résultats disponibles, on a effectué une analyse étendue et soigneuse des résultats des essais au vérin plat ; en même temps on a effectué une comparaison avec les mesures de contrainte initiale (effectuées par la méthode CSIR-doorstopper), avec les résultats des essais de charge à la plaque.

On a aussi employé une méthode d'élaboration simplifiée des mesures de déformation grâce aux résultats obtenus d'un modèle d'éléments finis tridimensionnel. D'après cette étude et d'après les comparaisons mentionnées ci-dessus on a mis en évidence la fiabilité des mesures au vérin plat *in situ*.

1. Introduction

The state of stress and the deformability of the rock around the contour of a tunnel or of an underground structure can be simply and quite successfully measured by means of the flat-jack technique.

The results thus obtained are generally through simple formulae inferred from the elasticity theory for a homogeneous and isotropic medium under plane stress conditions (Alexander, 1960). The boundary conditions are generally quite complex, and the interpretation of the data obtained *in situ* by the flat jack with simple schemes raised some doubts as to its reliability, and has prompted the search for alternative interpretation schemes, with particular reference to numerical methods (Bonvallet *et al.*, 1977; Wittke, 1977; Borsetto, 1982).

The aim of this paper is to clarify the validity and accuracy of the results provided by the traditional interpretation of the measurements made with the flat jacks on the basis of an extensive and attentive analysis of the results obtained through 60 tests carried out during six geomechanical investigations performed in Italy for the construction of five large underground power plants by ENEL (Italian Electricity Board) and for the study of the foundation rock of a dam (Fig. 1).

Three of these plants (Entracque, Piedilago, Edolo) are located in the Alpine region in metamorphic rock and the other two (Taloro and Solarino) are respectively in Sardinia in granite rock and in Sicily in soft sedimentary rock (calcarenites). The site of the arch-gravity dam (Ridracoli) is in the northern Apennines and the foundation rock consists of an alternation of marls and sandstone layers.

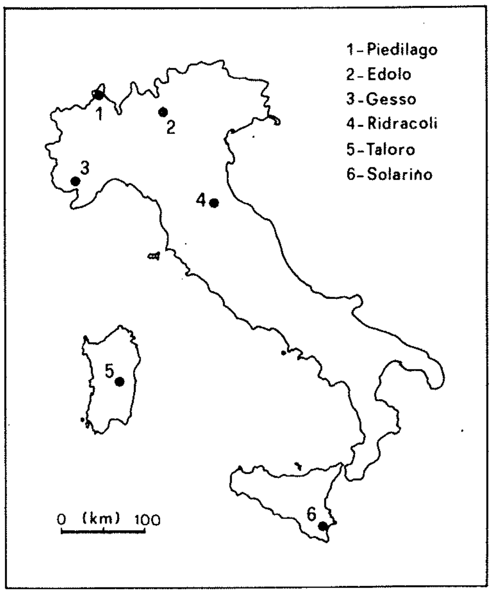

Fig. 1: Map of Italy showing the examined sites.

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**Experimental Institute of Models and Structures (Ismes), Bergamo (Italy).

2. Test technology

Fig. 2 illustrates the scheme adopted by ISMES (Institute for experimental Models and Structures) for the flat-jack tests performed in the examined sites. The slot, 1.1 m long and 0.6 m deep, is obtained by means of a series of overlapping holes, ϕ 64 mm, and the drill is provided with a guiding device (Fig. 3). The flat jack, 1 m wide and 0.5 m deep, is cemented to the slots. Convergence measurements are taken between the couples of points, located symmetrically on either side of the slot. The measuring pins scheme adopted in the Gesso and Taloro sites was: a = 0.2 m, b = 0.4 m, and c = 0.6 m. The experience thus acquired suggested the adoption of a final measuring pins scheme where: a = 0.3 m b = 0.6 m and c = 0.9 m.

The measuring pins consist of rigid rods, 0.35-0.40 m long, fixed over the central part of the flat jack by means of mechanically expanding bolts.

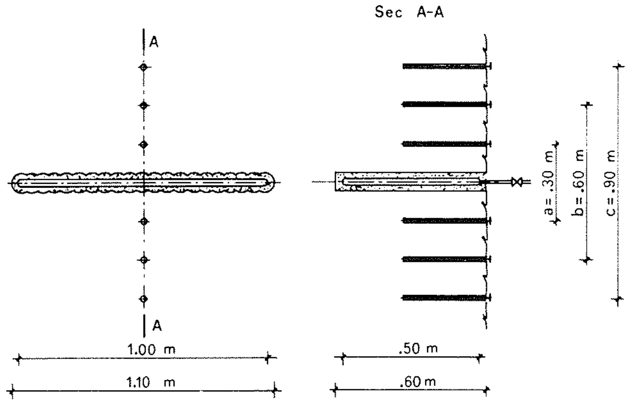

Fig. 2: Flat-jack and measuring pins scheme.

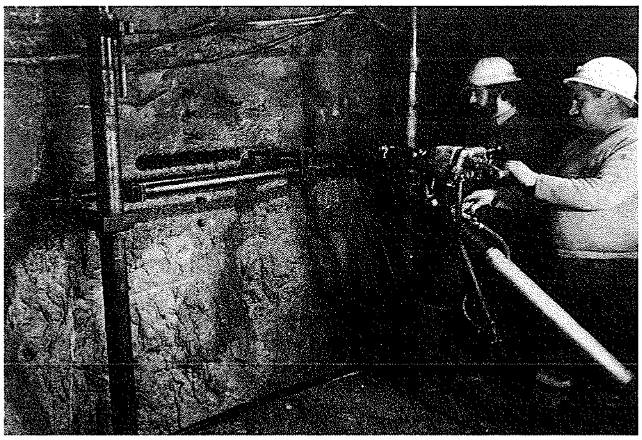

Fig. 3: Horizontal slot being driven.

In the former sites the measurements were taken by means of a mechanical gauge of the removable type (DEMEC); later displacement transducers mounted on an external rigid metal structure, were adopted, and those provide independent measurements of the absolute displacements of the six pins orthogonally to the plane of the slot (Fig. 4).

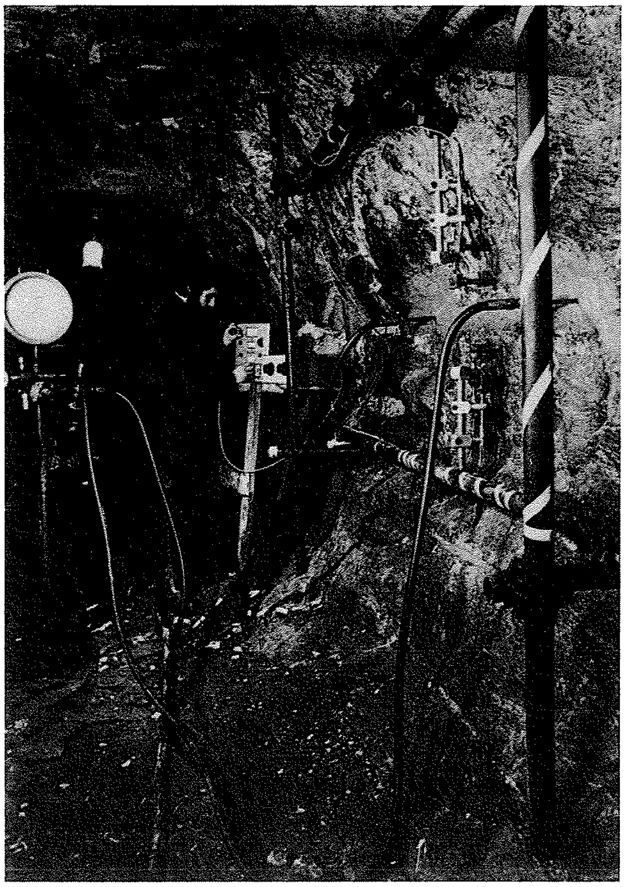

Fig. 4: Assemblage of devices for measuring displacements.

3. Analysis of the stress measurements

If the rock of the adit or tunnel where the flat jack tests are carried out has an elastic behaviour during the excavation, the distribution of the tangent stress near the wall is a function of the original stress tensor and of the geometry of the excavation (Fig. 5) and so the measured recovery pressure can, in this case, be interpreted as a medium value of the distribution of tangential stresses which correspond, in the considered stretch, to the depth of the slot.

If the strength of the rock involved by the test is not compatible with the stresses induced by the excavation, a plastic deformation of the excavation will occur. In such a situation the distribution of the state of stress around the excavation, and thus the value of the recovery pressure of the flat jack, will be a function of the residual strength of the rock (Fig. 5). In this case the measurements provided by the flat jack cannot give information about the original state of stress.

The stress measurements provided by the flat jack are not self explanatory in that they do not give any indication about the original state of stress, or about the mechanical behaviour of the rock mass. It is possible to obtain an answer only by a cross-analysis of the results provided by an appropriate set of geomechanical investigations as for instance: measure of the original state of stress, deformability measurements (e.g. by means of plate-loading tests), convergence measurements, micro-seismic investigation on the walls of the tunnel (Martinetti, 1980).

Something similar to this approach has been done by a comparison between the values of the state of stress measured by horizontal flat-jack tests and the values of twice the principal vertical stresses ($2\ \sigma_v$) determined along the plane normal to the axis of the tunnel (obtained from the *in situ* natural stress measurements performed with the CSIR-doorstopper method, in the vicinity of the area where the flat jack tests were performed) under the assumption that the rock mass has an elastic behaviour (Table I).

SITE	OVERBURDEN (m)	RECOVERY PRESSURE (σ_{rec}) (MPa)	ORIGINAL VERTICAL PRESSURE (σ_v) (MPa)	$\frac{\sigma_{rec}}{2\sigma_v}$
GESSO	87	2.8	4.7	0.30
	210	6.3	4.7	0.65
	260	14.1	6.1	1.16
	380	17.0	7.3	1.16
	312	42.3	7.3	2.90
TALORO	115	22.3	3.0*	3.70
	220	11.7	5.7*	1.03
	226	6.1	5.4*	0.52
	233	2.0	6.0*	0.16
	234	2.1	6.1*	0.17
	248	27.5	9.0	1.53
	248	22.3	9.0	1.24
	248	13.9	9.0	0.77
EDOLO	360	10.3	13.0	0.40
	380	15.0	13.0	0.58
	380	14.0	13.0	0.54
	380	8.9	13.0	0.35
PIEDILAGO	400	31.3	7.0	2.23
	400	17.0	7.0	1.21
	485	32.6	7.0	2.33
	485	23.6	7.0	1.69
	495	22.2	7.0	1.59
	495	27.9	7.0	1.99
SOLARINO	250	10.0	5.8	0.86
	250	15.3	5.8	1.33
	250	8.3	5.8	0.73
	250	10.0	5.8	0.86

* Values estimated by the overburden pressure in the measurement points of the flat-jack tests

When the original state of stress was not available the comparison was made by estimating the original state of stress as the value of the overburden pressure at the points where the flat-jack tests were performed.

In Table I there are three different basic situations:

– The measurement of the recovery pressure with the flat-jack is in agreement with the values of twice the original vertical stress. For instance in the Solarino site the identification process from the investigations performed led to the conclusion that the rock mass still performed elastically during the excavation of the drift.

– In the Edolo site and in some tests at the Gesso site and the Taloro site the ratio $\sigma_{rec}/2\ \sigma_v < 1$ clearly shows that there has been yielding in the rock around the tunnel. In this situation the σ_{rec} measured with the flat jack can be usefully used in the evaluation of the residual strength parameters of the rock mass (Borsetto, 1980). In particular as regards the Edolo site the stresses measured by the flat-jack were compared with the original state of stress, with the deformability characteristics and with the measured convergence deformations, and this comparison led to the identification of the residual strength parameters of the rock mass (Forzano, 1979).

– For the Piedilago site the ratio $\sigma_{rec}/2\ \sigma_v$ proved to be greater than one. This inconsistency may be due to the strong anisotropy of the rock that requires a more refined interpretation model. The tests showed that the deformations measured at the end of the cut for each couple of pins are not always recovered during the recovery stages, with a single identical pressure value (Fig. 6), the deviation from the means value of the three recovery pressures for each single couple of pins is however not highly significant as can be seen in fig. 7.

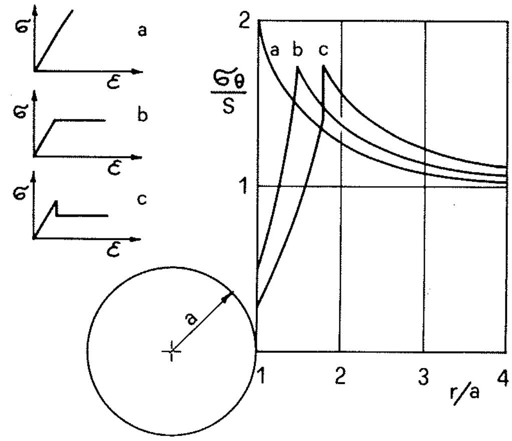

Fig. 5: Tangential stress scaled down to the natural stress around the tunnel as a function of the mechanical behaviour of the rock: a) elastic b) elasto-plastic c) strain-softening.

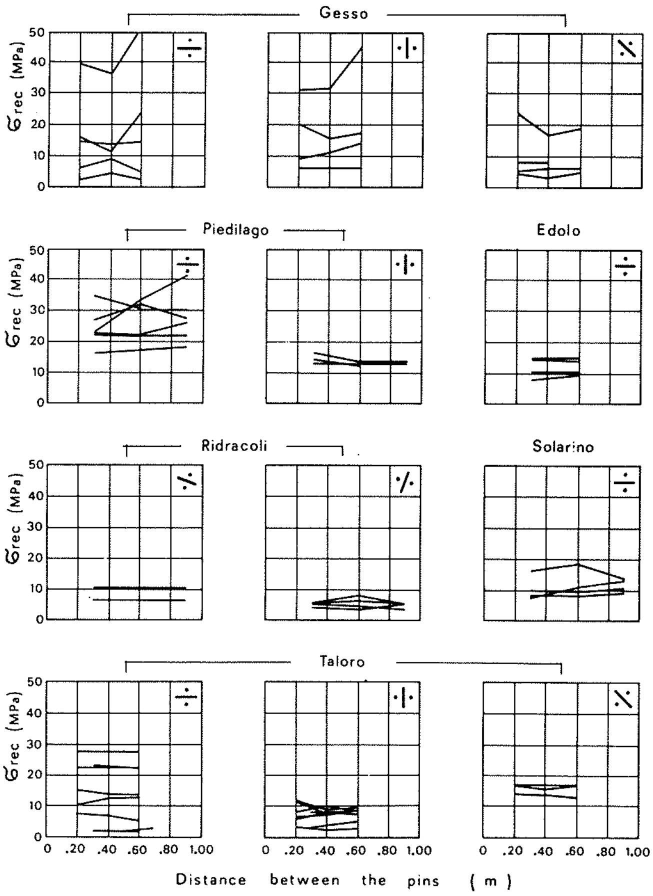

Fig. 6: Average recovery pressure versus the distance of the measuring pins.

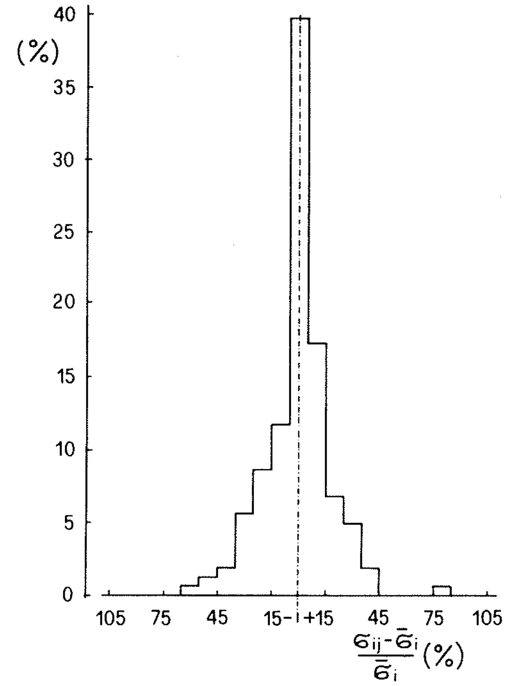

Fig. 7: Histogram of the deviation from the mean values scaled to the mean values of the recovery pressure for a single test.

4. Analyses of the measures of deformability

The flat jack tests are generally carried out in a zone which is often loosened due to the excavation and to yielding. For the sites examined in this paper the analysis of the results of the investigation carried out systematically and in particular the plate-loading tests with 3 m long multipoint extensometers, the sonic log along boreholes and the microseismic investigation along the walls of the tunnel all showed that there is in general a layer of loosened rock whose thickness is between 0.25 and 0.80 m from the boundary of the tunnel. In many cases it is therefore impossible, with the flat-jack tests, to evaluate the deformability of the undisturbed rock mass. The analysis of the results obtained from the application of Alexander's formula to the deformation measured for each couple of pins, shows a trend which generally increases with the distance from the slot (Fig. 8). This can be explained very likely by the fact that the interpretation makes references to plane stress conditions; this schematization is probably too different from the actual situation for the pins are at a greater distance from the slot. On the other hand, the use of measuring pins at some distance from the slot is of particular importance because of the large amount of rock involved by the tests.

The meaningfulness of the value of the elasticity modulus calculated as harmonic mean of the values relevant to the three couples of pins proved not to be fully acceptable as the distribution of the deviations is slightly asymmetric (Fig. 9). The value of the mean quadratic deviation is 30 %.

Enel and Ismes are jointly carrying out a programme of study and research, which is still in progress, with the aim of developing the technological and interpretational know-how of flat-jack tests.

A tridimensional elastic, isotropic and homogeneous finite element model of a tunnel having the same geometric schemes as the flat-jacks used *in situ* was developed by Ismes. This model allows to evaluate the effects of the cut of the slot, of the recovery of the deformations and of the rotation of the rods holding the pins (Borsetto *et al.,* 1983) and has led to a different approach with respect to the usual formula.

On the basis of the results obtained by the abovementioned F.E. model, the following simplified expression was devised to express the secant elastic modulus:

$$E = \frac{\delta_{mod}}{\delta_{meas}} \sigma_{rec} = \frac{(\delta_v + l \operatorname{tg}\alpha)}{\delta_{meas}} \sigma_{rec} \qquad (1)$$

where : δ_{mod} is the overall displacement occurring during the pressurization of an ideally efficient flat-jack;

δ_{meas} is the displacement measured during the in situ pressurization;

σ_{rec} is the in situ recovery pressure;

δ_v is the vertical displacement occurring during the pressurization of an ideally efficient flat-jack;

ℓ is the length of the rods holding the pins;

α is the angle of rotation of the rods holding the pins.

Expression (1) was used to reprocess all the tests performed. The results showed lower E values (Fig. 10) and a better distribution of the deviations (Fig. 11) both in terms of

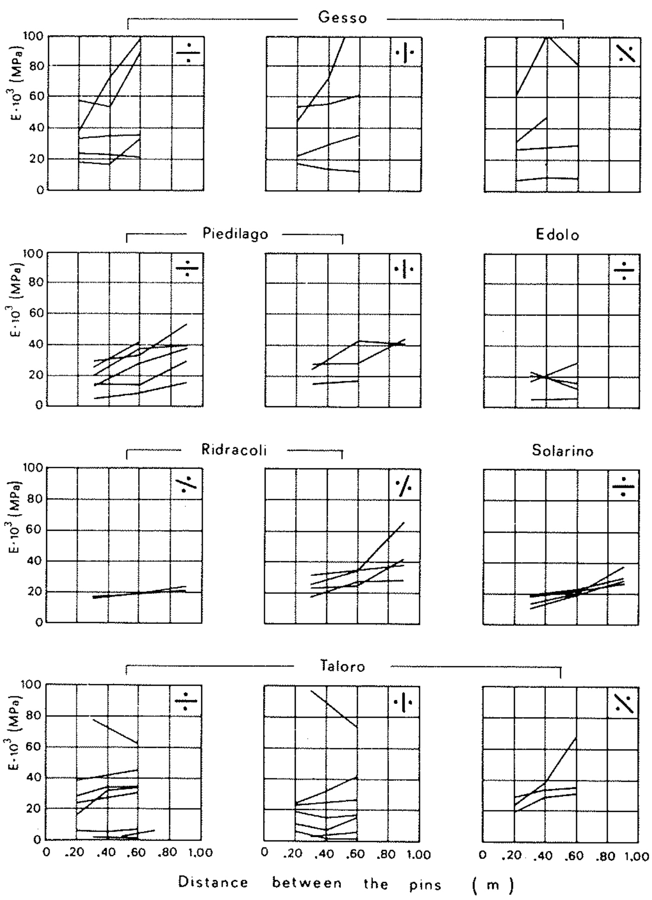

Fig. 8: Average elastic moduli computed with Alexander's formula versus the distance of the measuring pins.

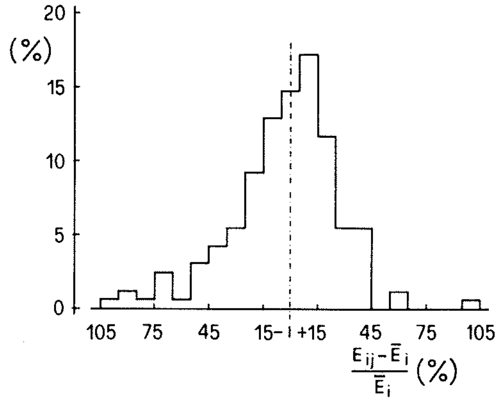

Fig. 9: Histogram of the deviation from the mean values $(E_{ij} - \bar{E}_i)$ scaled to the mean values $(\bar{E}_i)$ of the elastic modulus computed with Alexander's formula.

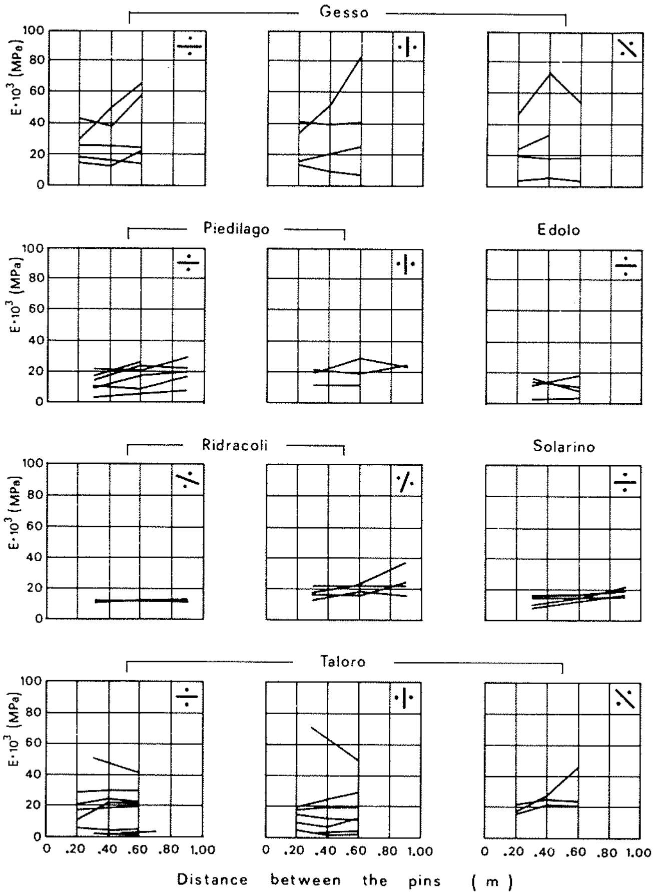

Fig. 10: Average elastic moduli computed with the FEM moduli versus the distance of the measuring pins.

symmetry and of the mean quadratic deviation (25 %) as compared with the results obtained by using Alexander's formula (Figs. 8 and 9). Expression (1) can be considered as a usual formula which keeps account of the tridimensional aspect of the actual test. On the basis of this concept a graph was worked out (Fig .12) whereby the E modulus provided by expression (1) can be directly calculated starting from the elasticity moduli determined with Alexander's formula.

The reliability of the E values determined with the flat-jack tests was assessed by comparing them with the E values obtained with the plate-loading test, whereby the deformations of the rock are measured at different depths below the plate (Manfredini *et al.*, 1975), which proved very reliable. In particular, a comparison was made between the deformability parameters determined by the flat-jack test through the different abovementioned eleborations and the deformability values determined through the plate-loading

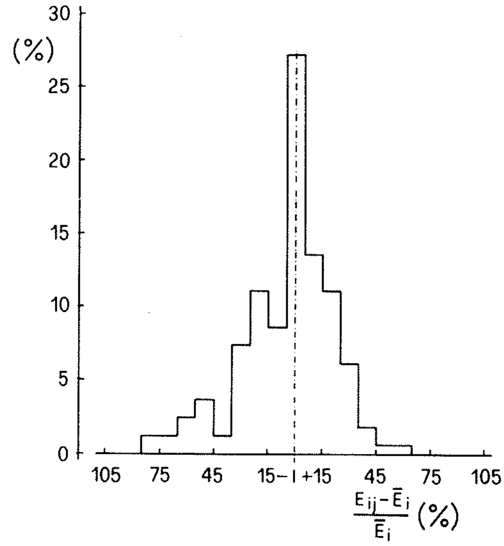

Fig. 11: Histogram of the deviation from the mean values scaled to the mean values of the elastic modulus computed with the FEM formula.

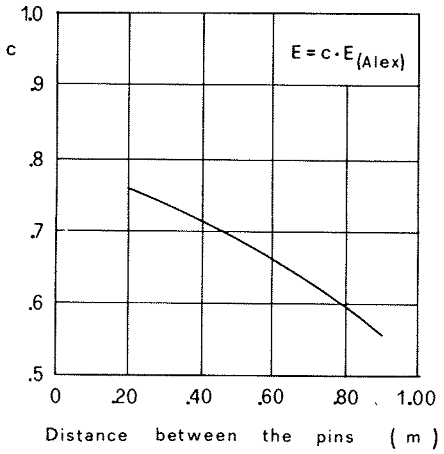

Fig. 12: Graph for determining the FEM elastic modulus from E as obtained using Alexander's formula.

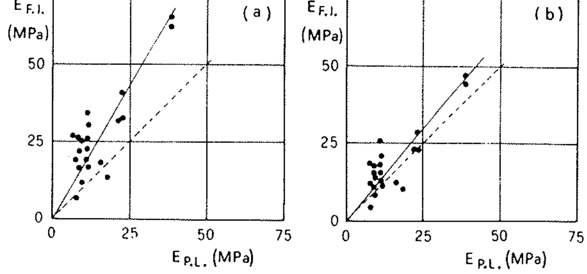

Fig. 13: E modulus evaluated by Alexander's formula (a), and by the FEM formula (b), versus E modulus obtained through plate-loading tests.

tests (carried out in areas very close to the flat-jack tests) for a depth from the edge of the tunnel of the same order of magnitude as the depth of the flat-jack test (about 0.5 m).

The mean values of E determined through the flat jack tests are on average higher than those obtained by the plate-loading tests (Fig. 13). The improvement obtained by using formula (1) is self-evident.

5. Conclusions

The reliability of the stress measurements obtained by the flat-jack tests is very good. As regards the meaning of the values obtained, the tests performed with a flat-jack do not provide an exhaustive answer. Therefore, in order to interpret the results, a cross-analysis with information obtained from other *in situ* tests is necessary.

As to the evaluation of the deformability of the rock mass, it was observed that in many cases the measurements made with the flat-jack involve a more or less thick yielded rock layer, and therefore, in this case, they cannot provide data about the deformability characteristics of the undisturbed rock mass. However, the E values obtained with the flat jack tests can be usefully used in the design of structures where the knowledge about the deformability of the yielded rock layer is most important e.g. the design for the lining of pressurized hydraulic tunnels.

The E values determined through the usual interpretation formulae proved to be quite scattered and overestimated as compared with the more reliable E values determined by the plate-loading test. Such scatter and overestimation have been considerably reduced by merely using an interpretation scheme that takes into account the tridimensional aspect of the problem.

In view of the advantages provided by the flat-jack tests further efforts will be made to improve technologies used for carrying out the test (e.g. cut of slot methodology, new measurement devices for the direct measurement of the deformations at depths of 0.25-0.30 m, by using special proximity transducers) and to improve also the interpretation of the results by using numerical methods and constitutive laws which are more appropriate and which better fit the real behaviour of the rock.

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