Investigations of Tunnel and Penstock Linings in Anisotropic Media

Etude des parois des tunnels et des conduites forcées dans les milieux anisotropiques

G. OBERTI, F.A.S.C.E., PROF. DR. ENG., *Head, Department of Civil and Structural Engineering, Polytechnic Institute, Turin, and Director, I.S.M.E.S., Bergamo, Italy*

E. FUMAGALLI, PROF. DR. ENG., *I.S.M.E.S., Bergamo, Italy*

SUMMARY

The authors have recently studied structural problems relating to tunnels and penstocks placed on more or less stratified rocks. In this paper they present some considerations of characteristics of orthotropic bodies capable of simulating the anisotropy of stratified rocks. They also describe a few test procedures used at I.S.M.E.S., Bergamo, for solving this type of problem by means of two-dimensional models.

SOMMAIRE

Les auteurs qui ont étudié récemment des problèmes statiques relatifs au percement de tunnels et conduites forcées dans des roches plus ou moins stratifiées, jugent utile de présenter quelques considérations sur les caractéristiques des systèmes orthotropiques qui peuvent représenter l'anisotropie des roches stratifiées. Ils profitent de l'occasion pour présenter la technique expérimentale adoptée à I.S.M.E.S. de Bergame pour la solution de ces problèmes par des modèles à deux dimensions.

THE DETERMINATION OF THE SIZE of concrete or reinforced concrete linings for highway, railway, and pressure, or penstock, tunnels in rock is based on the physico-mechanical characteristics of the rock mass they are to penetrate. As is known, the loading exerted on the lining by the surrounding ground or more or less stratified rock is related not only to the morphological homogeneity and isotropic features of the materials penetrated and to their physical characteristics (cohesion and internal friction) but also to their mechanical properties (elastic, plastic, and viscous) which in time modify the loading patterns.

The tunnelling procedures and the speedy placement and completion of the lining are of basic importance so that no time is left for the rocky mass to undergo settlements which modify the pre-existent state of the equilibrium of the whole system and thus increase the intensity of the loading action on the lining. Moreover, in most cases the rocky mass is sharply stratified and therefore in theoretical or experimental design studies it may still be schematized as an "orthotropic" rock system. However, it can seldom be considered as homogeneous and isotropic, as it is, at present, generally assumed to be when calculating the size of the lining to be adopted.

In some particular cases it is possible (and rational) to reduce the anisotropy of the rock system by grouting, thus forming around the lining a ring of rock of limited extent in which the mechanical and isotropic conditions are greatly improved. This can be proven by testing *in situ* experimental galleries which reproduce the actual structure. One can thus determine whether the classic formulae for linings (Lamé type) may be adopted, extending them beyond the lining proper to the grouted ring of surrounding rock and then reducing the check of the anisotropic effect of the external mass of rock to that ring alone.

Finally, the influence of the deformability of the designed lining deserves attention. If this deformability is greater than that of the tunnelled rock, plastic or internal friction slidings of the external rocky mass are possible. On the other hand, a lining whose rigidity in every direction is the same as that of the rock, placed inside the tunnelled section, would entail pressure conditions practically identical with those which existed in the rock prior to tunnelling.

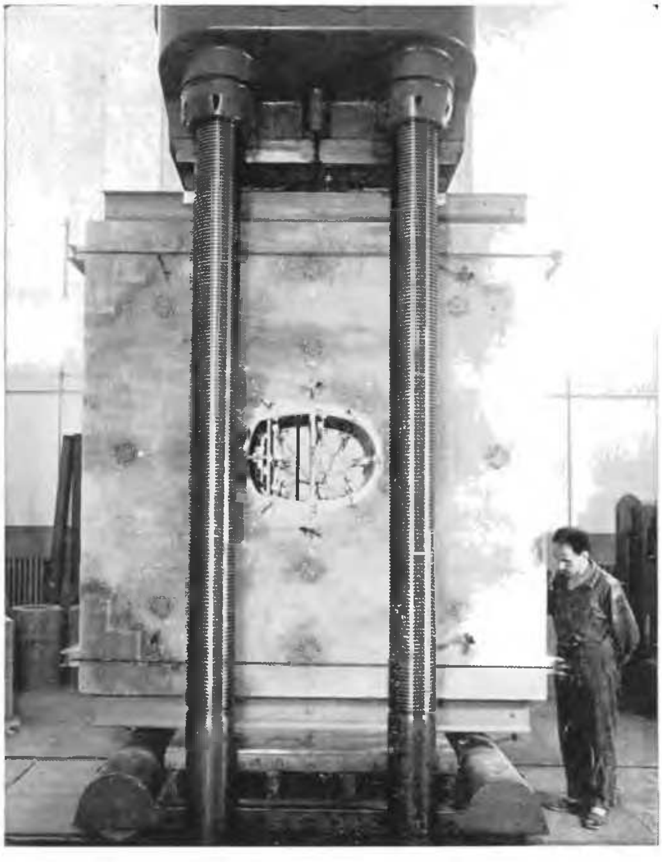

FIG. 1. Model of Cisa Pass tunnel. General view during horizontal tests.

TESTS PERFORMED ON TWO-DIMENSIONAL MODELS

The model tests reported below concern two cases of tunnel linings. The consideration of the results obtained will clearly show the possibilities presented by experimentation.

FIG. 2. Model of Cisa Pass tunnel. Cracks after failure tests under loading applied at 45°.

Tunnel at the Top of the Cisa Pass Expressway

The tunnel crosses Apennine formations of varying composition. The mechanical characteristics of the ground are limited by the following two conditions: (*a*) calcareous, satisfactorily isotropic rock whose modulus of elasticity $E = 100{,}000$ kg./sq.cm., with cohesion 40 kg./sq.cm., and coefficient of internal friction $\varphi = 45°$; (*b*) marly-clayey material whose cohesion < 1 kg./sq.cm. and coefficient of internal friction $\varphi \simeq 20°$.

A scale of 1:20 was chosen. For case (*a*), a 280 by 280 by 75 cm block of a pumice-cement mix having the required characteristics was used. A model of the lining, also of a pumice-cement mix, was placed at the centre of the block. The efficiency ratio between the deformability and strength features of the prototype and those of the model was assumed to be $\zeta = E_p/E_m = 5$. The loading was applied by means of the 2,000-ton compression testing machine available at I.S.M.E.S. Fig. 1 shows in detail the technique used. In order to check the static behaviour of the lining under variously inclined compressive actions, the block reproducing the homogeneous rock was subsequently uniformly stressed in the three basic directions, vertically, horizontally, and at 45°. Finally, the model was tested to failure by stressing it at 45° (Fig. 2).

For case (*b*), a rigid reinforced concrete tank had to be built to contain the lateral pressures of the low-cohesion marly-clayey material. This material was reproduced employing a sand-bentonite mix whose mechanical characteristics corresponded to those *in situ*. In this case it was necessary to adopt an efficiency ratio $\zeta = 1$.

The measurements essentially concerned strains and stresses as well as internal deformations. For the former, mechanical and electroacoustic extensometers were used and for the latter, comparators and removable instruments.

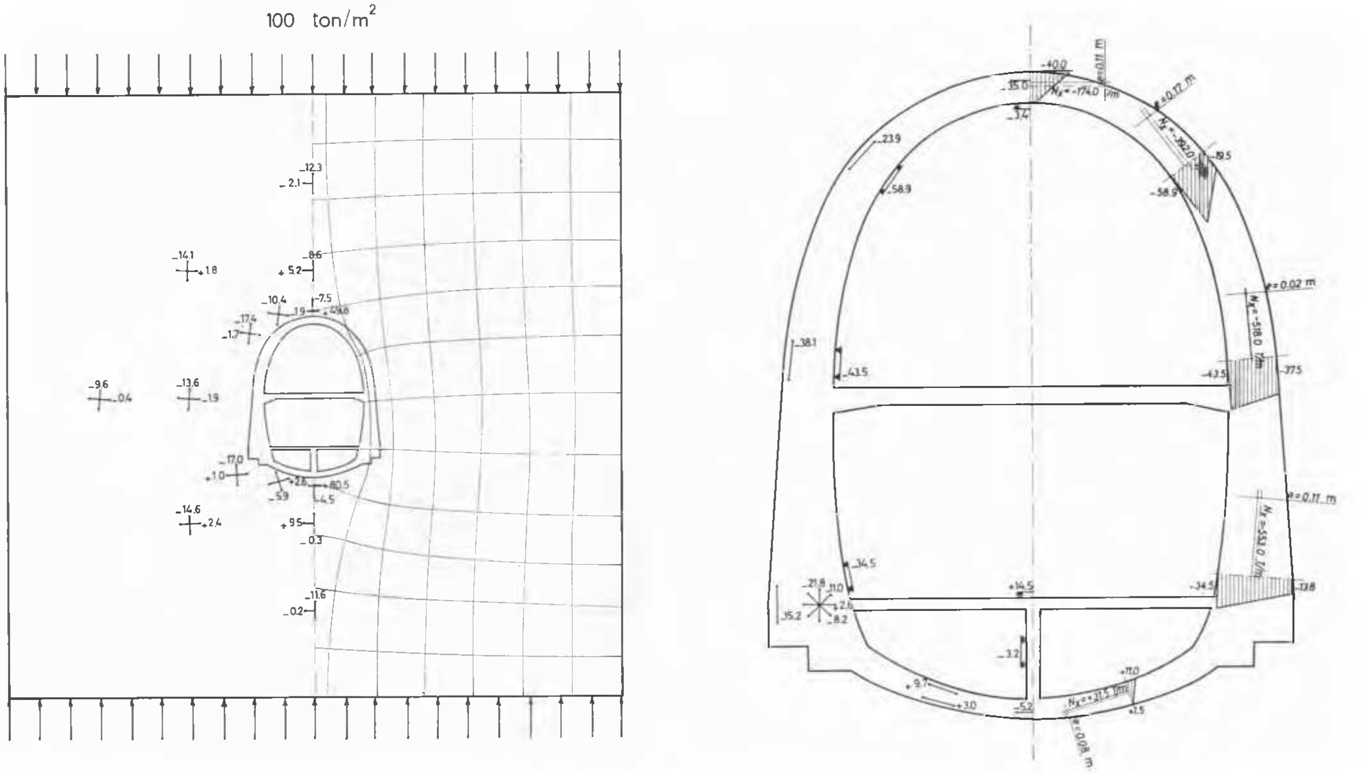

FIG. 3. Model of Cisa Pass tunnel. Results of tests under vertical loading (100 ton/sq.m.). Excavation in calcareous rock. Principal stresses and isostatic lines in the rock; stresses and resultants in the lining.

Fig. 3 shows the most significant test results for case (*a*) under vertical stress conditions. Their analysis indicates in particular the disturbance in the stress pattern within the rock produced by the presence of the tunnel. The lining at the crown of the tunnel cross-section is strongly compressed, thus differing sharply from the overlying rock which in the horizontal direction is in a considerable state of tension so that under a uniform load of 100 tons/sq.m. it is already stressed to the breaking point. Of interest also is the behaviour of the lower arch which, when considered as connected to the flooring slab (chain) and to the central diaphragm (strut), recalls the performance of a truss.

The results obtained for the low-cohesion material of case (*b*) showed in the lining states of stress not much different from those caused by the action of an external hydrostatic load.

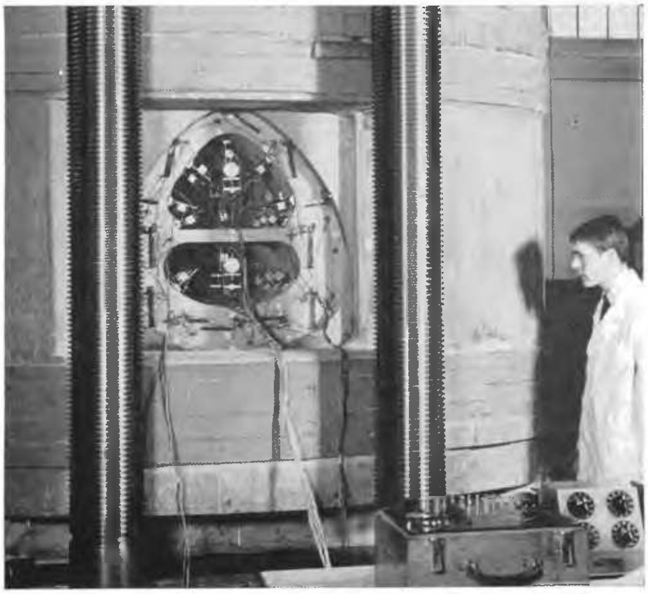

FIG. 4. Model of the bottom discharge tunnel of the Salagou Dam. General view of model under test.

*Bottom Discharge Tunnel of the Salagou Rockfill Dam**

In this case the material pressing against the lining was the loose rockfill of the dam. The problem was of interest both in itself and because of the analogy between it and problems of tunnels crossing zones of recent landslides. For over one-third of its height the tunnel is situated on the dam foundation rock. The plane model of the tunnel on its foundation bed was built to a 1:12 scale, and the efficiency ratio assumed for the materials was $\zeta = 3$.

The testing installation, save for some appropriate adaptation, did not differ from that used for the Cisa Pass tunnel crossing low-cohesion marly ground (Fig. 4) except that the pressing soil was replaced by calcareous gravel of suitable size reproducing the dam material. The tests and the measurements were carried out very carefully, and the designed structure was improved through a series of tests on two models, the second of which represented the modified design (Fig. 5).

The basic questions that could be answered by the model test results were: (1) What was the structural contribution and, in general, the performance of the tie-slab placed at half the height of the tunnel, taking into account the deformability of the latter within the framework of its hyperstatic connection to the external ovoidal structure? (2) What was the distribution pattern of the tunnel loading on the foundation ground? (3) What was the pattern of the pressure exerted on the lining by the loose material? In order to answer question (3), the tie-slab and its connections were removed from the first model upon completion of its testing under working conditions, leaving only the basic ovoid in the model. Extensive measurements on the ovoid by means

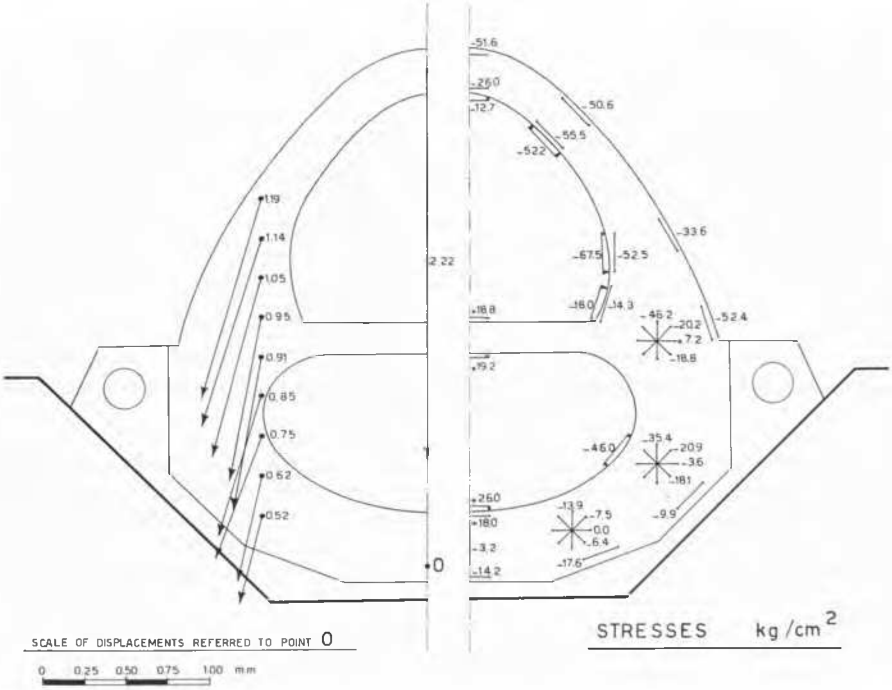

FIG. 5. Model of Salagou tunnel. Test results under uniform vertical loading (120 tons/sq.m.). Stresses and displacements referred to point 0.

---

*Investigation promoted by Les Travaux Souterrains, Paris, under the supervision of engineer V. Bauzil, Compagnie Nationale d'Aménagement de la Région du Bas-Rhône et du Languedoc, Nîmes.

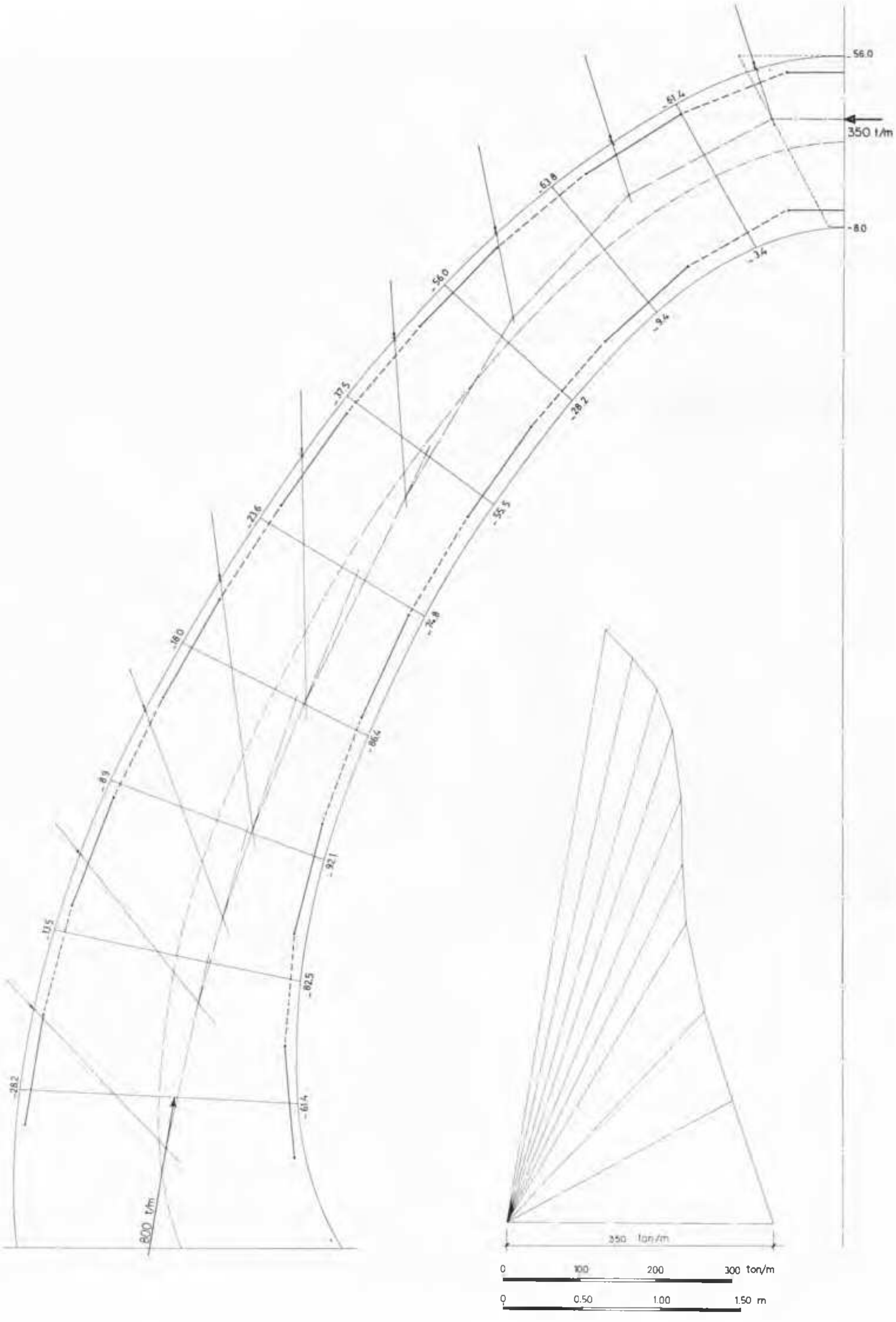

FIG. 6. Model of Salagou tunnel. Rock pressure against lining under uniform vertical loading (120 tons/sq.m.).

of a thick network of extensometers made it possible, through graphical elaboration and by finite quantities, to obtain the pattern of the above-mentioned pressure, conforming quite satisfactorily to the resultants measured in the lining and to their eccentricities (Fig. 6). The model results also showed that the upper connections between the ovoid and the tie-slab had to be somewhat thickened, whereas the thickness at the crown of the lower inverted arch had to be reduced. These local modifications made it especially possible to reduce the stresses wherever they were locally pronounced.

PROBLEMS OF MODELLING IN ANISOTROPIC ROCK

Let us for the time being consider only the simplest case of anisotropy, that is orthotropy, represented in nature by rock formations in parallel beds. In this case, reproduction on plane models of three-dimensional deformation processes requires that the impeded transverse deformations $\epsilon_z = 0$ be taken into account.

In the presence of low-cohesion material, this can be complied with by making use of a rigid containing tank similar to the one described above, and reducing to a minimum the friction between the material and the containing walls of the tank. Good results are obtained by applying to those walls a layer of grease a few millimeters thick covered by a polythene sheet. In the case of highly cohesive materials, preference is given to plane models having a surface freely deformable in the transverse direction, i.e., $\sigma_z = 0$. This is also done in order to permit reading the deformations at the surface of the model rock material.

In the linear elastic range, whenever the value of Poisson's ratio of the rock can be predicted, the three basic parameters, with the reference axes oriented in directions perpendicular and parallel to the bedding, are represented by the moduli E_x, E_y, G_{xy}. When the stratification is formed by thin interlayered beds having poor mechanical properties, the ratio E_y/E_x is determined by the axial deformability and the thickness of the interlayered beds, whereas the cohesion and angle of friction features of the interlayered material decisively affect the tangential elastic modulus G_{xy}.

At the limit, an anisotropy having a ratio $E_y/E_x = 1$* may be obtained. Interlayered sedimentary, low-cohesion, and very compact or water-saturated material (slime, clay, peat sediments, etc.) can undergo changes in shape only, not in volume, and therefore can produce tangential deformations only. The case described can therefore show the influence and importance that the transverse deformability characteristics may acquire in an orthotropic system and their degree of independence of the normal deformability features.

Less frequently, stratification is presented by alternate beds of different nature. In such a case, assuming that the contact between the beds is perfect and indicating with E_1, E_2 and t_1, t_2 the elastic moduli and the thicknesses of the respective alternate strata in the y direction we have:

$$E_x = \frac{t_1 E_1 + t_2 E_2}{t_1 + t_2},$$

$$E_y = (t_1 + t_2) \Big/ \left(\frac{t_1}{E_1} + \frac{t_2}{E_2} \right),$$

$$\frac{E_y}{E_x} = \frac{t_1^2 + 2t_1 t_2 + t_2^2}{t_1^2 + t_1 t_2\left(K + \dfrac{1}{K}\right) + t_2^2},$$

where K is indifferently E_1/E_2 or E_2/E_1.

A circumstance in which anisotropy by stratification may give rise to problems sharply differing in practice is given by the relationship between the thickness of the beds and the extent of the structural problem. While a mass of thick rock beds may, in its over-all performance, comply with the laws of orthotropy, a hole driven in that material must take into account the manner and the frequency of its cutting through the various beds. As a limiting case, a small hole made in a thick bed of sound and isotropic rock may, owing to the wholly local and moderate disturbance it produces, be considered as made in entirely homogeneous and isotropic material.

Now, the great variety of conditions present in nature and the extreme difficulty often encountered in solving analytically the problems relating to them clearly show the importance of experimental investigation with models. This is all the more evident when one considers that the reproduction of a rock system with the geomechanical features of the materials composing it may, at the present state of our knowledge and experience, be carried out with satisfactory fidelity, even though in a schematized form. Obviously, the determination of the rock characteristics necessitates an extensive and exhaustive programme of research. The investigation has to be divided into two entirely distinct parts, one of which is capable of defining the anisotropic features of the whole, for instance, the ratio E_y/E_x between the normal moduli, and the other consisting in laboratory experimentation on specimens of the materials. Tests on the deformability and failure by sliding for various ratios τ/σ make it also possible to determine the cohesion and angle of friction of the interlayered material.

Generally speaking, notwithstanding the numerous tests that may be performed, omitted here for brevity's sake, tests on materials alone can hardly yield an adequate knowledge of the over-all performance procedure of a rock system. For this reason, reproduction on a model of the (usually isotropic) individual layered materials with their characteristics is the most reliable method of simulating any deformation process in a rock system to be investigated. Naturally, in this case it is necessary by means of tests on elementary modelled structures, for example, composite blocks, to see to it that the basic anisotropy features such as the ratio E_y/E_x be conformed to.

FIG. 7. Geomechanical model of Grancarevo Dam. Reproduction of the abutment rock.

On the other hand, the experimental research carried out in the past few years at I.S.M.E.S. on the reproduction of rock systems has made it possible to raise the modelling technique to a high level of specialization, finding in the geomechanical models of dams a wider and more complex field of application.

In this connection, Fig. 7 shows the reproduced abutment rock of the Grancarevo Dam, Montenegro, for which some 13,000 blocks of various sizes were used. The blocks were arranged in layers of various thicknesses and inclinations, with interposed material corresponding to that *in situ*, in order to comply with the friction and contact conditions between the blocks and, more generally, with the anisotropic features of the entire rock system.

CONCLUSION

The conclusion to be drawn is that, in order to develop and improve the technique of excavating and lining of tunnels and penstocks in rock, two things are necessary. On the one hand, testing *in situ* must be expanded so as to gain a more thorough knowledge of the characteristics of the field materials; and, on the other hand, greater reliance is to be placed on laboratory experimentation with models, which alone seems to be a most trustworthy tool for investigating the equilibrium and the over-all performance of rock systems.

---

*Equality of moduli in this case occurs only for pairs of values relevant to directions that are orthogonal to one another.