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Hydraulic fracturing testing method for rock stress measurements in Italy

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ABSTRACT The in situ stress measurements in Italy performed up to the present by means of the CSIR "doorstopper", have evidenced complex geological features of the single earth's regions, changing from one place to another. More recently, consideration has also been given to hydraulic fracturing, with the interest to use this technique in rock engineering for the design of large cavities and tunnels. The results obtained so far by laboratory tests on rock specimens and modeling materials are illustrated in the present paper. Also mentioned are the first in situ applications related to fields other than stress measurements, and future developments of the research work being carried out.

RESUME La détermination de l'état de contrainte dans le massif rocheux éffectuée jusqu'à présent en Italie au moyen de la technique de décompression du CSIR "doorstopper", a mis en évidence une situation géologique très complexe changeant de lieu en lieu. Plus récemment on a envisagé d'utiliser la technique de la fracturation hydraulique pour projeter de grandes excavations souterraines et de tunnels. Dans ce rapport on présente les résultats obtenus au laboratoire sur des échantillons de roche et de matériel artificiel. On mentionne aussi les premières applications de cette technique non reliées à la mesure de l'état de contrainte et les développements prévus pour le futur.

ZUSAMMENFASSUNG Die Bestimmung des Spannungszustandes im Fels, die bisher in Italien mit der CSIR "doorstopper" Überbohrtechnik ausgeübt wurde, hat ein stark veränderliches Verhältnis der Geologie bewiesen. Kürzlich ist die hydraulische Felsfrakturierung für die Untertagehohlraumen- und Tunnelsentwürfe in Betracht genommen worden. In diesem Bericht werden Ergebnisse von Laboratorium-Experimente auf Fels- und Modellproben vorgelegt; die ersten Anwendungen, die nicht mit Spannungszustand verbunden sind, und die vorgesehenen Entwiklungen werden ebenfalls erwähnt.

1. INTRODUCTION

In the past twenty years, rock stress characterization for design and construction of underground cavities and tunnels acquired increasing importance, because of more complexity of problems and applications being considered, increased depth of new tunnels being excavated, modern technologies of rock excavation and reinforcement systems being used (Barla and Mahtab, 1983).

Also, the past experience does not translate into practical judgement and the function of some of the underground openings (such as storage cavities) may involve questions of long-term stability under coupled, thermal, mechanical, and hydrological environments. Finally, numerical methods of analysis of structures in rock are well advanced and require quantification of the rock mass characteristics to an unprecedented degree of sophistication and confidence.

In Italy, where the territory is highly characterized by the presence of hills and mountains in a most irregular pattern, the same problem of identification and quantification of significant properties of rock mass, expecially for rock stress determination, has become relevant and stringent in a number of design projects dealing with underground construction (Barla,1985). On the contrary, rock stress measurements were carried out mostly in underground structures near to the surface by means of CSIR "doorstopper" and flat-jack methods, often resulting in irregular and uncertain stress distributions with depth. With this in mind, an effort has been made recently to approach the HYDRAULIC FRACTURING technique as a tool to be used in rock engineering practice for the purpose of rock stress determination.

2. ROCK STRESS MEASUREMENTS IN ITALY

In order to give a perspective of the main geological features of the single earth's regions of Italy, reference is made to the large scale division of the lithosphere into major tectonic units (AGI, 1985). In fact, depending on the distinctive features of these major tectonic units, geological investigations and rock mechanics studies, including rock stress measurements, will be characterized by substantial methodological differences and results. At the same time, the extrapolation of rock stress data from one site to another is to be considered with great caution and in most cases it becomes even impossible.

Given the effects of a long tectonic evolution, the present geological features allow one to subdivide the exposed portion of the earth's crust into two large structural units: (i) Tectonically active alpine-type fold belts (mountain chains, forming 10÷15 percent overall); (ii) Platforms (forming 80÷90 percent of the land). Secondary suprastructures such as rifts, molasse troughs, intramontane basins, etc. complete the group of major tectonic units.

i) <u>The alpine-type fold belts</u> formed during repeated orogenic cycles from Upper Cretaceous to Pliocene, and are still in an uplifting phase (Neotectonics). Lithostratigraphic sequences of considerable thickness including typical rock types (turbidites, cherts and siliceous shales, etc.) from the chain frame. Such sequences have been deformed by general intense tectonics. A low grade metamorphism and volcanism developed on the inner side of these chains. Seismic activity is a peculiar feature of the alpine-type fold belts.

ii) <u>Platforms</u> consist of two distinct planes: a basement of folded old rocks, and an upper part (or cover) formed by flat-lying, slightly deformed or undeformed sedimentary formations. Ancient and young platforms can be distinguished. The basement of ancient platforms consists of intrusive and metamorphic rocks of Prepaleozoic times, whereas the basement of young platforms consists of Paleozoic intrusive, metamorphic and sedimentary rocks of fold mountain chains which formed during the Caledonian (430÷340 MA) and Hercynian (280÷225 MA) orogenic cycles. The sedimentary formations have the same characteristics as those typical of alpine-type fold belts such as elongated basins, lithostratigraphic sequences, intense tectonic deformations, etc. The covers of ancient and young platforms consist of almost flat-lying slightly deformed Paleozoic and Mesocenozoic (ancient platforms) and Mesocenozoic (young platforms) continental or neritic formations. Mild folds some hundred to some thousand kilometres in radius are peculiar structural forms.

This summary of the distinctive features of major tectonic units would show that geological characteristics of two sites may either differ greatly, or have much in common, depending on whether the sites, independently of their mutual distance, belong to the same or to different structural units.

These different geological characteristics seem to be well emphasized in terms of rock stresses by the results of in situ measurements performed in Italy over the last fifteen years (Martinetti and Ribacchi, 1980). By using the CSIR "doorstopper" method, measurements were carried out in underground power-plants and some important mines (Fig. 1), thus covering different geological conditions, structural setting and morphological features.

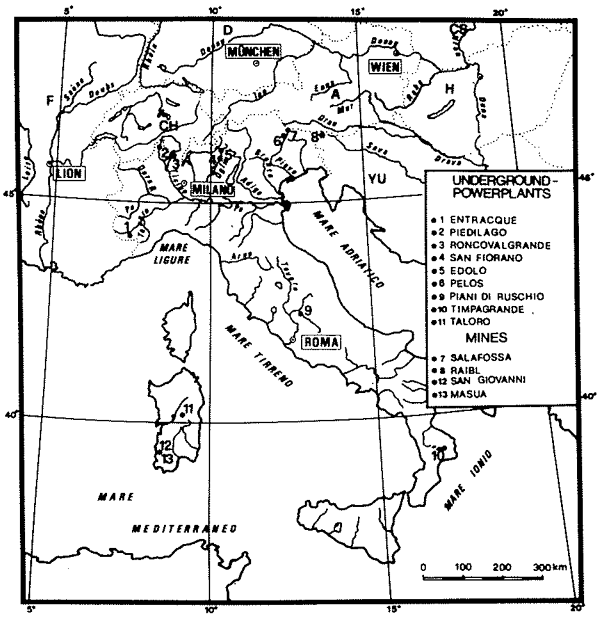

Fig. 1 - Location of sites in Italy where in situ stress measurements have been carried out.

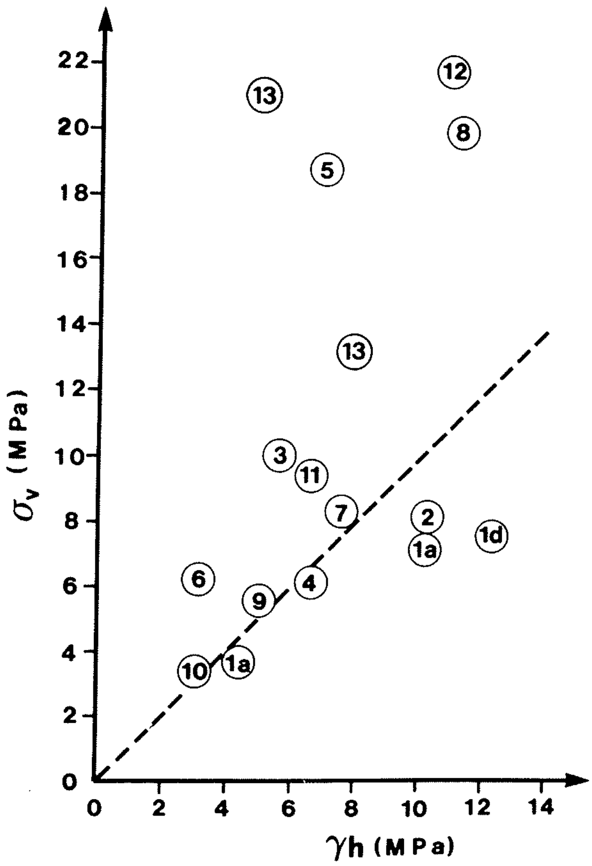

Fig. 2 - Vertical stress in the test sites versus overburden pressure.

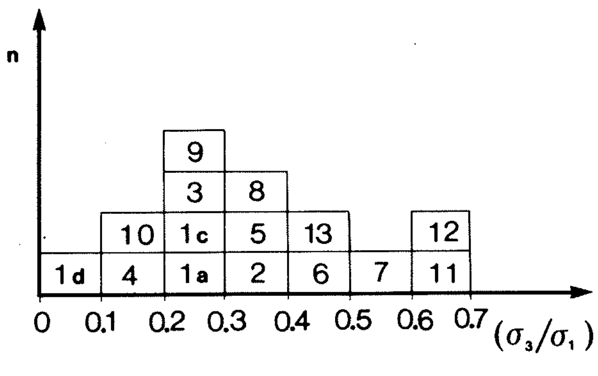

Fig. 3 - Histogram of the ratio between minimum and maximum principal stresses.

According to the illustrations reported in Figures 2 to 4, the following observations are made (Martinetti and Ribacchi, 1980):

- In mountain slopes or buttresses, the inclination of the maximum stress in the vertical section falls between that of the slope and the vertical. This is in agreement with the theoretical evaluation of the stresses that are generated within the rock mass following the excavation of the valley.
- The vertical stresses σv are mostly equal or greater than the γh values that can be calculated on the basis of the overburden thickness h . Theoretical

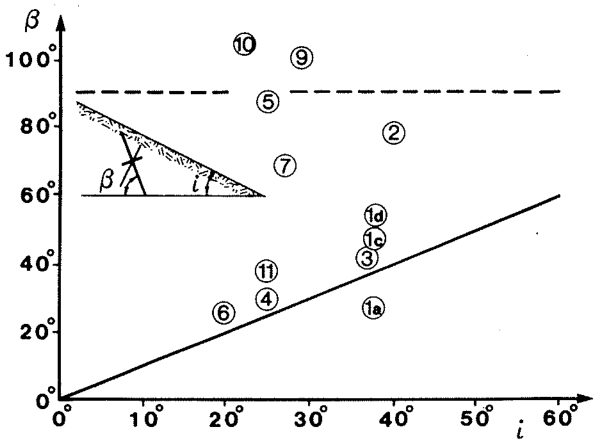

Fig. 4 - Inclination β *of the greater secondary stress versus slope inclination i.*

analyses carried out by assuming either elastic or elastoplastic behavior of the rocks show that in correspondence to a slope, σv should be somewhat higher than γh.

- In the Raibl, S.Giovanni and Masua mines, the vertical stresses are by far greater than those corresponding to the overburden. For the first case, this is certainly due to the measuring site being located on the floor of a valley which is surrounded by high mountains; for the second site, it is more difficult to supply an explanation. At the Masua mine the results are affected by the vicinity of the testing site to the mine openings.
- The principal secondary stresses, on the horizontal plane are often oriented according to the axis of the valley. In some istances (Roncovalgrande, S.Fiorano, Edolo) the longitudinal component is considerably high; on the other hand, in the Timpagrande site, the deep incision of the two valleys that isolate the buttress which includes the measuring zones, justifies the low values of this component. Finally, the high values of the horizontal stresses, in the Raibl mine must be pointed out; they are probably one of the factors that account for the rock bursts occurring in the mine.
- The values of the ratio between minimum and maximum principal stresses vary within a very wide range; however for most cases they fall within the 0.15÷0.40 range. The lower limit of this ratio is determined by the limit strength of the rock mass, corresponding to the long-term strength of its weaker elements (more highly fractured zones, faults).

3. THE APPROACH TO HYDRAULIC FRACTURING

As stated above, the information presently available in Italy on the state of stress in the earth's crust, given the complex geological features of its territory, does not allow to draw satisfactory conclusions on possible general trends, as related to different regions or tectonic units. At the same time, the need to obtain reliable data on the in situ stresses in rock masses, where important underground structures (i.e. hydroelectric projects, deep tunnels in the Alpine and Appennines regions) need be constructed, is becoming very clear.

In most cases, the assumption of geostatic conditions, as introduced in the initial design, are misleading with respect to shape, size and orientation of underground openings, so as to render any change during the actual excavation very expensive. This fact, related to the disadvantages common to the indirect methods for rock stress measurements (i.e. CSIR doorstopper) such as:

- the difficulty and expenses associated with driving pilot or access tunnels in the area of a planned underground cavity;
- the depth of the tunnel to be designed, which can be reached only by means of boreholes drilled from the surface;
- the point measurements which involve very small areas;
- the need to measure the elastic parameters to convert measured strain to stress;
- the effect of highly differential stresses where overcoring could

produce discing of rock;

made it imperative to look for a possible application of HYDRAULIC FRACTURING to rock engineering, in the design stage of underground cavities and tunnels.

The hydraulic fracturing technique (Haimson and Fairhurst,1970) is not affected by the disadvantages mentioned above. The same equipment to be used down the hole may be simple and not very sophisticated, mainly in the depth range of interest in civil engineering projects.

The method consists of sealing-off a section of a borehole at the required depth by two rubber packers, and hydraulically pressurizing the packed-off segment. When the breakdown pressure is reached, the rock surrounding the borehole fails in tension and develops a fracture. This fracture can be extended away from the hole by continuous pumping. When pumps are shut off with the hydraulic circuit kept closed, a shut-in pressure is recorded. This is the pressure necessary to keep the fracture open. The breakdown and shut-in pressures can be related to the prevailing stresses on site. A commercial impression packer is finally used to determine the exact direction and inclination of the hydrofracture. In this manner, both the magnitudes and the directions of the principal stresses can be evaluated. The hydrofracturing technique can be used in deep holes or in short holes around tunnels.

For example, taking a site of a planned underground hydro project, the hydrofracturing technique can be used directly in exploration holes drilled into the general area of the planned caverns (Haimson,1984). Thus, no additional expenses are needed for drilling special holes for stress measurements. Moreover, the stresses are estimated as part of the preliminary investigation before the actual design, causing no delays, and requiring no design changes. If necessary, overcoring tests can also be carried out later on, when the pilot or access tunnels are excavated. They can provide a check on the hydrofracturing results and increase confidence in the stress boundary conditions used in design. Also, it is to remark that traditionally the shape of the tunnels and caverns and their orientations are decided early in the design process, while overcoring measurements are conducted considerably later.

The different factors mentioned above prompted us to start a research program on HYDRAULIC FRACTURING, oriented to stress measurements for rock engineering purposes. At present, consideration is given mostly to laboratory testing on rock specimens (cylindrical shape) and on modeling material (cubic shape); equipment has being set up and is due to be tested in the field.

The purpose is to gain confidence with the hydraulic fracturing concepts, by verifying the theoretical relationships holding true between rock stress and pressures recorded during testing. Also, in view of applying the technique in a thermal environment (Geothermal Fields), testing was extended to thermal conditions.

4. LABORATORY TESTING

A number of factors are known to influence the results of theoretical interpretation of field data. The following are considered to be of interest:

- hole diameter;
- rock tensile strength;
- fluid viscosity and rock permeability;
- stiffness of the packers;
- flow and/or pressurization rate;
- thermal conditions (for deeper holes);
- interaction between induced fractures and rock with preexisting joints (Zoback et Al.1977), which are often met during excavation in Italy;

and are being investigated throghout laboratory testing.

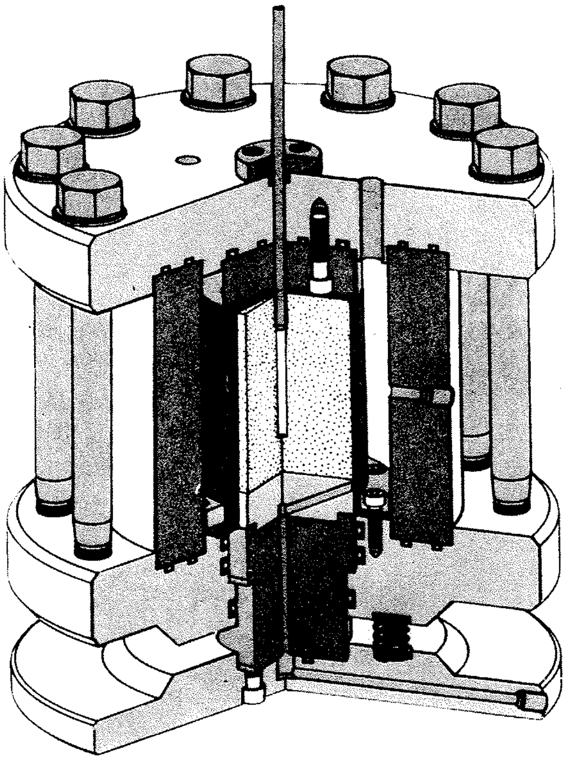

Fig. 5 - A partly sectioned, isometric view of the triaxial cell used for testing rock specimens.

4.1 Testing on rock specimens.

A triaxial cell to be used under a hydrostatic confining pressure up to 75 MPa and a vertical stress (applied by a 5 MN loading machine), in a temperature range from 18° to 200°C, has been designed and developed at the ENEL-CRIS Rock Mechanics Laboratory (Figg. 5,6).

Rock specimens, 80 mm in diameter and 100 mm in height, can be tested; each specimen contains a hole 8 mm in diameter, to be used for injecting the fluid for the hydrofracturing process. The inlet tube is sealed with a special resine, at the top of the specimen; in a similar way, the plug at the bottom is also sealed, in order to obtain the same stiffness at both ends of the hole. The chamber surrounding the rock specimen (encapsulated by a sylicone membrane) is obtained by a steel hollow cylinder, closed at its ends by means of two flanges. These are locked by ten vertical tie-rods, which allow for tests to be performed in conditions where the

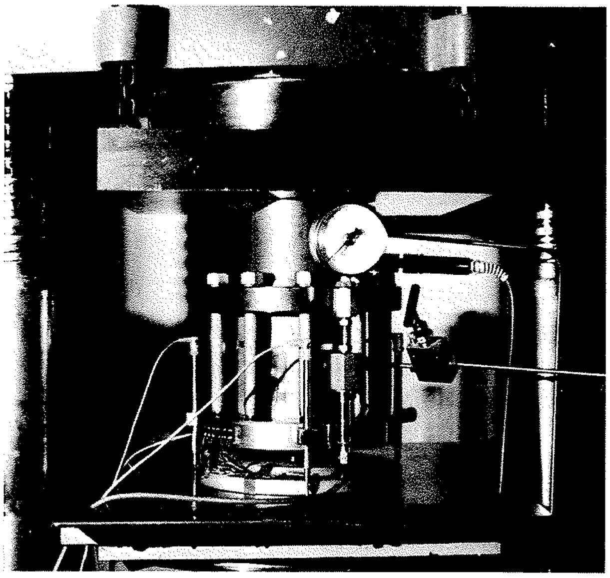

Fig. 6 - The cell between the plates of the 5 MN loading machine.

lateral stress is greater than the vertical stress. An hydraulic system is used to apply the lateral and hydrofracturing pressures (up to 140 MPa) to the rock specimen.

In all cases, the pressure gradients are controlled very carefully, with a number of transducers being mounted so as to measure the pressure in the cell and near to the fluid injecting tube.

The rock specimen can be gradually heated, according to the desired heating cycle, chosen before testing. Two different systems have been set up for this purpose. Either heating elements near the specimen, like a furnace inside the cell (ten group-connected thermo-resistances for gradually heating in order to avoid shocking the rock), or a heating exchanger, external to the cell, can be used. A number of controllers and thermosensors are applied for monitoring. Also, vertical loading and different pressure conditions (lateral and hydrofracturing pressures) are controlled and continuously plotted during testing.

The results of a typical test, carried out to reproduce the hydrofracturing phenomenon under high temperature and pressure conditions, is shown in Fig.7 (test performed with the pressurization

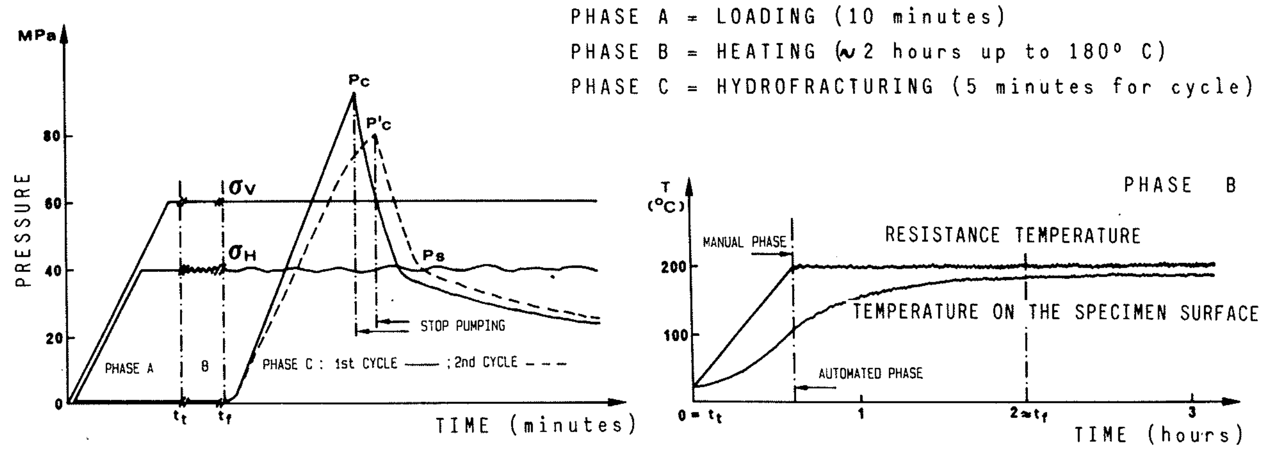

Fig. 7 - The results of a typical hydrofracturing test.

rate control). With a given state of stress (σ_v=vertical stress; σ_h = σ_h max = σ_h min = horizontal stress) applied to the specimen, the heating cycle is started, so as to obtain gradually (5÷7°C/min) the desired temperature. With steady state conditions being reached, water is injected in the specimen center hole; the pressure conditions are continuously monitored in order to know the stress-path which is applied during testing.

Particular attention has been devoted to the method for immediately stopping pumping, when the peak pressurization value is reached. The inlet pressure is electronic filtered and stored for a comparison with a very small prefixed step of pressure in real-time. At the peak value, when a sudden decrease of pressure is reached, a relay releases a pneumatic actuator, which is positioned on the delivery side, to stop fluid pumping. Consequently, the equilibrium conditions ps = σ_h can be attained. The test is then repeated with a new pressure cycle, to obtain the lower limit pressure p'c. It is known that the two peak values pc and p'c allow one to measure the rock tensile strength σ_t = pc - p'c, for the conditions being reproduced during testing. A tonalite specimen after hydrofracturing is shown in Fig.8.

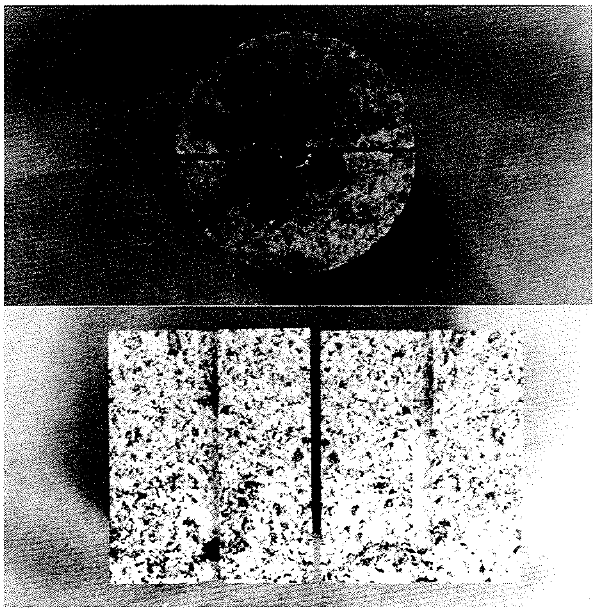

Fig. 8 - A Tonalite specimen after hydrofracturing.

4.2 Testing on modeling materials.

True triaxial stress conditions are being investigated at the Rock Mechanics Laboratory of ISMES, Bergamo, by using cubic specimens 180 mm in side. The hydraulic fracturing tests are performed on a modeling material (i.e. obtained by means of mixtures of chalk-celite and water), giving a uniaxial compressive strength σ_c = 1.32 MPa. This material is shown to exhibit a linear elastic behaviour up to brittle failure. A very viscous fluid is being used as hydrofracturing fluid, given that the modelling material is pervious.

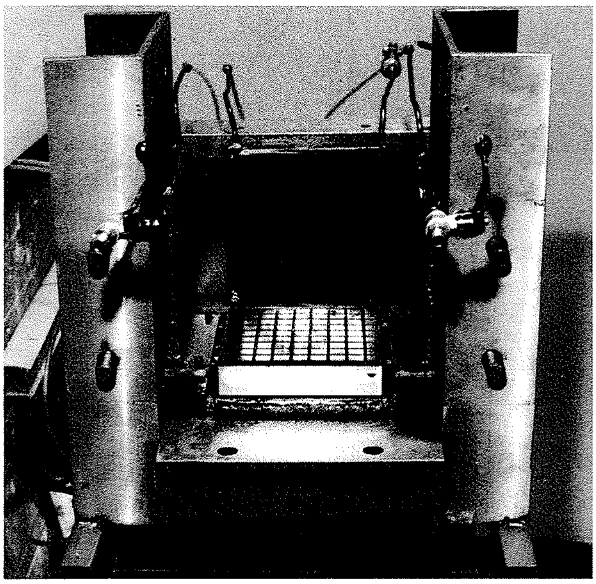

Fig. 9 - A view of the triaxial device used for testing modeling materials.

This is the opposite of what is assumed for in situ testing (impervious rock with water as hydrofracturing fluid), however the results are comparable satisfactorily.

A stiff metallic frame and six flat jacks allow for the application of a triaxial state of stress on the cubic specimen being tested (Fig. 9). An interfaced gas-oil lung is used to keep the stresses constant during testing. Pressures transducers are being applied for measurement and control. A soft plate, provided with prismatic neoprene elements and no-friction teflon papers, is inserted between the flat jacks and the specimen, thus giving a uniform pressure distribution on each plane surface.After loading the specimen, the hydrofracturing fluid is injected into a vertical hole in the specimen. The inlet pressure is measured and monitored by means of a computer, which is programmed to stop immediately the pumping phase, when the breakdown pressure is reached. This provision in testing is extremely important in order to avoid fracture propagation.

A number of tests have been performed to verifying the following influencing factors and test conditions, under different stress states (Fig.10).

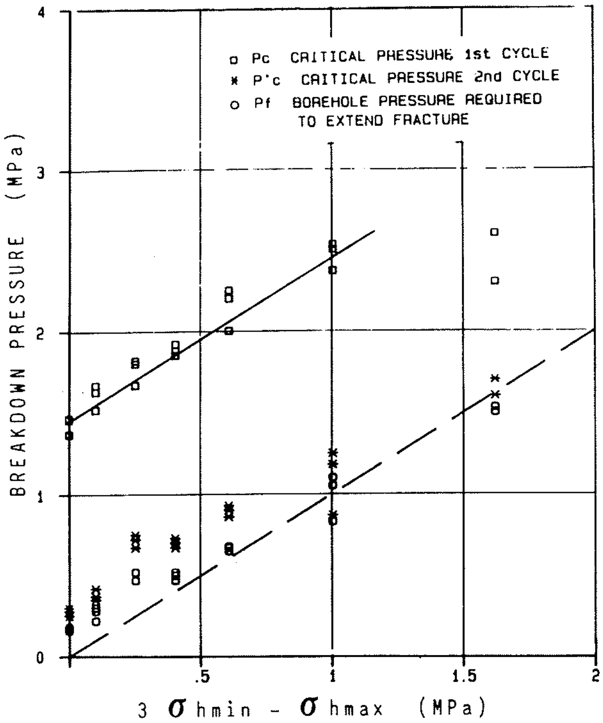

Fig.10 - Relationship between breakdown pressure and horizontal stresses.

- Lining of the internal hole with rubber or sylicone membrane, or epoxy-resine, has been studied in order to obtain an impermeable hole up to the fracture initiation, without sudden elastic energy release due to stiffness inadequacy of the lining itself.
- Fluid viscosity has been investigated in a large range (from 27 to 10000 centistokes at 20°C), to simulate different permeability conditions (Figg.11,12); satisfactory results have been obtained by using glycerine.

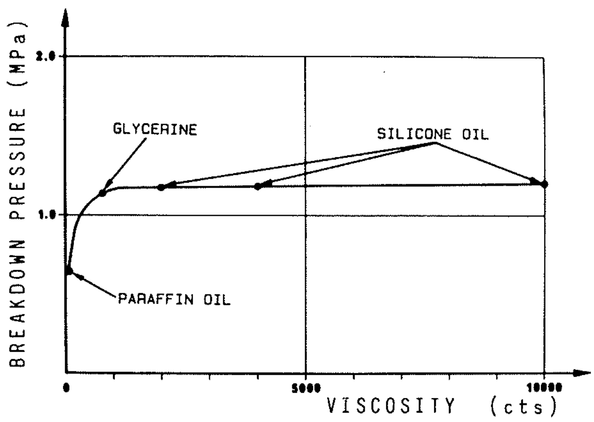

Fig.11 - Influence of fluid viscosity.

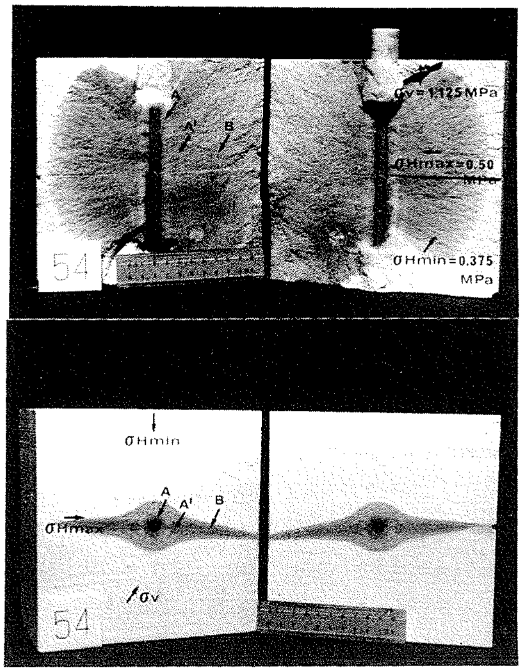

Fig.12 - Vertical and horizontal cross-sections of two model-specimens.

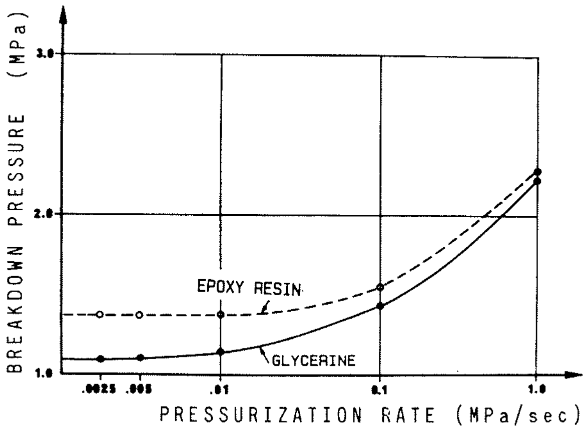

Fig.13 - Influence of pressurization rate on breakdown pressure.

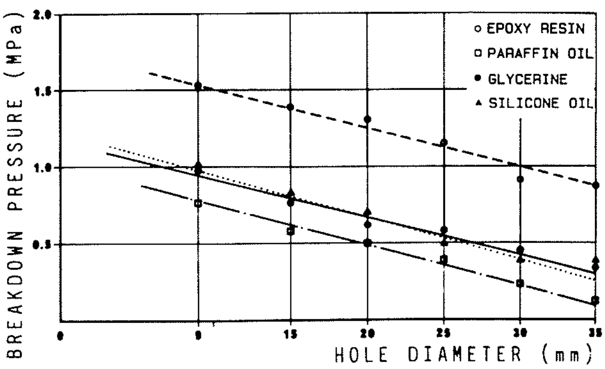

Fig.14 - Influence of hole diameter on breakdown pressure for different fracturing fluids.

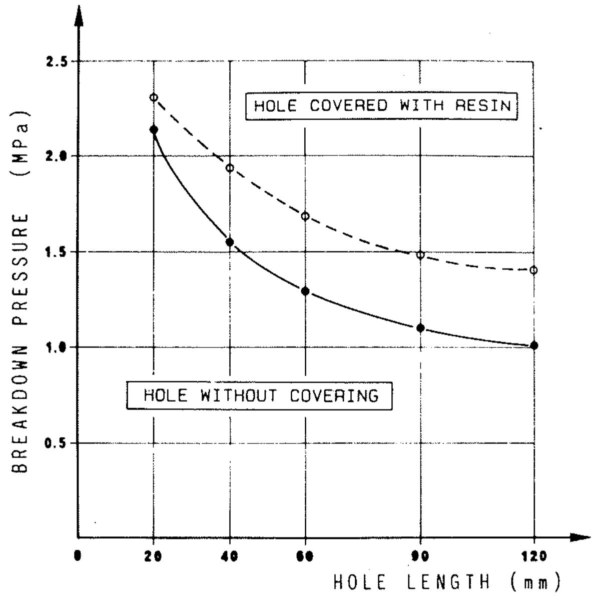

Fig.15 - Influence of pressurized hole length on breakdown pressure.

- Different pressurization rates ($2.5x10^{-3}$ ÷ 1 MPa/sec) have been analysed with respect to the breakdown pressure (Fig.13). Similarly, the flow rate effect has been investigated, by finding it to be negligible so as to carry out all tests under constant flow rate (3.3 cc/sec).
- Hole diameters and pressurized range extensions (Figg. 14,15 respectively) have been correlated with the specimen sizes: the results are in very good agreement with the experiences performed by other Authors.
- Particular attention has been devoted to the tensile strength of rock, obtained as difference between the first and the second peak pressure values, for different stress conditions, or by the hydraulic fracturing test itself without confining pressures being applied (σt=1.48 ±0.13 MPa against 1.45 ±0.15 MPa respectively).

5. IN SITU TESTING

The applications of hydraulic fracturing in Italy has been mostly oriented to the need of petroleum

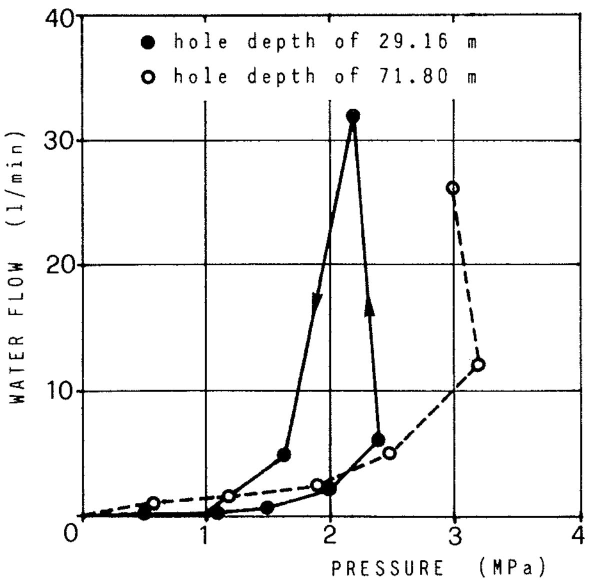

Fig. 16 - Water flow versus pressure as obtained at the Ridracoli Dam site.

industry and geothermal energy. However, a number of tests have been carried out involving the same technique in rock engineering, mostly with reference to the design of dam curtain grouting (Fig. 16) and prestressing of rock around tunnels. The experience gained in this manner is of help in the actual setting up of the equipment needed for in situ stress measurements.

The hydraulic fracturing tests performed by Consonda (Milan) at the Ridracoli Dam site, in holes 72 m deep, are of interest. As shown in Figure 16, these tests were directed towards measuring the maximum water flow absorption through the existing fractures in the rock mass, under different pressure levels. The purpose was to evaluate correctly the influence of wedging, squeezing fluid-fracturing, and compaction grouting in given field conditions.

6. CONCLUDING REMARKS

With the main purpose to increase the present knowledge of the in situ state of stress in Italy, as related to rock engineering (i.e. underground large cavities and tunnels), a testing equipment for hydraulic fracturing in situ is being set up. Possible applications are envisaged in the near future, in a site where previous measurements of the in situ state of stress were carried out by overcoring.

At the same time, the laboratory experimental work on hydraulic fracturing is being continued, with emphasis placed on the influence of factors such as preexisting joints and discontinuities, anisotropy. The hydrofracturing attitude at the hole contour and in the surrounding rock, in such unusual conditions, is to be investigated so as to help the interpretation of tests carried out in Italian rock complexes.

REFERENCES

A.G.I.1985. Geotechnical Engineering in Italy. Associazione Geotecnica Italiana on the occasion of the ISSMFE Golden Jubilee.

Barla G.and Mahtab A. 1983. Characterizing and Modeling Rock Mass for Design and Construction of Underground Cavities. Final Report on the Joint U.S. - Italy Workshop, Polytechnic of Turin.

Barla G. 1985. Rock Mass Characterization for Design and Construction of Underground Cavities and Tunnels. Geotechnical Engineering in Italy.

Haimson B.C.and Fairhurst C. 1970. In situ Stress Determination at Great Depth by Means of Hydraulic Fracturing. Proc.11th U.S.Symp.on Rock Mechanics. W.H.Somerton,ed.,AIME,559-584.

Haimson B.C. 1984. Pre-excavation In situ Stress Measurements in the Design of Large Underground Openings. ISRM Symp. on Design and Performance of Underground Excavation.Cambridge,U.K.

Martinetti S.and Ribacchi R. 1980. In situ Stress Measurements in Italy. Rock Mechanics, 31-47.

Zoback M.D., Rummel F., Jung R. and Raleigh C.B. 1977. Laboratory Hydraulic Fracturing Experiments in Intact and Pre-fractured Rock. Int.J.Rock Mech. Min. Sci. Vol. 14.