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Stress measurements in tunnel linings

(paper presented at International Symposium on *Field Measurements in Geomechanics,* Zürich, September 5-8, 1983)

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STRESS MEASUREMENTS IN TUNNEL LININGS

Giovanni Barla [1] and Pier Paolo Rossi[2]

1. Introduction

One problem in tunnel design is the measurement and interpretation of stresses in linings. The interest in engineering practice relates to the need for checking the lining behavior, in cases of malfunctioning or during the service life of the structure. Also, the evaluation of the static conditions of tunnels excavated in the past and supported with brick masonry linings is sometimes to be considered.

In the present paper, the techniques developed to measure stresses in the above conditions are described. Two practical cases are briefly examined. First, the measurements carried out in a concrete lining are discussed. The investigation allowed one to define a portion of the tunnel, where the support was considered to be overstressed. In conjunction with results of numerical modelling by the Finite Element Method, it was possible to suggest appropriate measures to be taken, in order to relieve the undesired stresses acting in the lining. Then, the results of measurements in a brick masonry lining of a railway tunnel are reported.

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2. Stress measurements in concrete linings

The measurement of the state of stress on the surface of a concrete lining in a tunnel is carried out according to the method shown in Figure 1. The procedure is as follows. Metal pads with a conical indent are fixed to the lining surface so as to form a 45 degree rosette (the initial distance between the metal pads ranges from 10 to 20 cm). A mechanical strain gage is then used to measure the distances across the four diameters (Step (1) in Figure 1, also see Figure 2). The concrete core with the metal pads cemented on it is then overcoved by using a thin-walled bit (Step (2) in Figure 1, also see Figure 3). As stress relief is taking place, the distances across the four diameters are again measured with the mechanical gage, up to the point when no stresses are considered to be present in the concrete core (Step (3) in Figure 1).

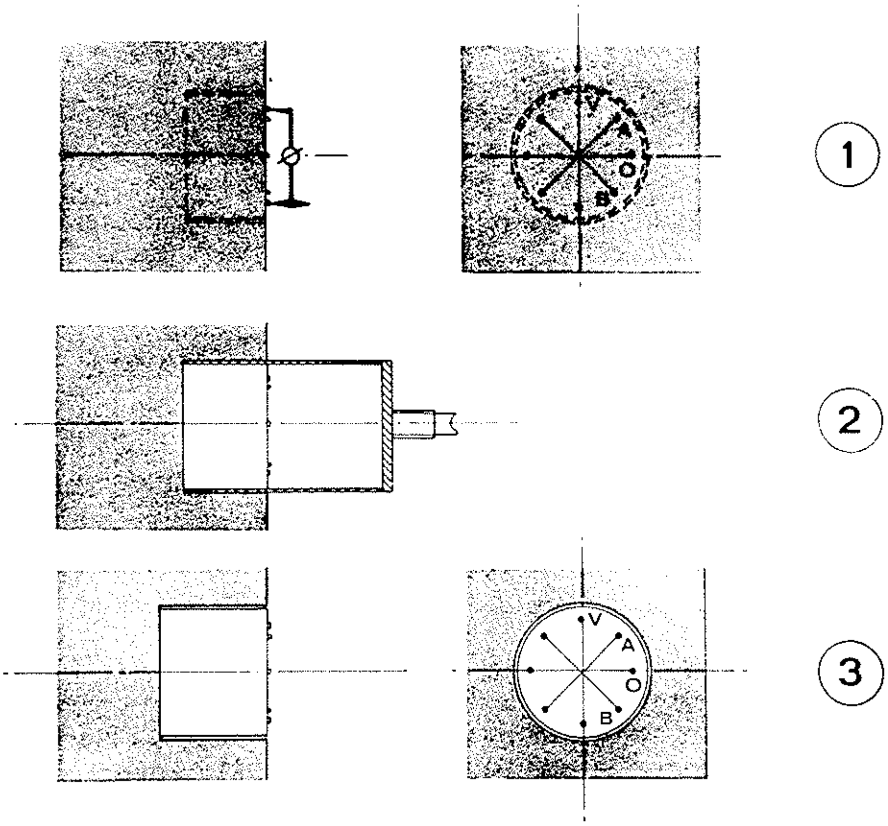

Fig. 1 Schematic representation of the method used for measuring stresses in concrete linings.(1) Measurements of distances across the diameters of the rosette. (2) Overcoring of a concrete core by a thin walled bit. (3) Surface rosette displacement measurements following stress relief by overcoring.

The changes in distances across the four diameters give the strains (ε_V, ε_O, ε_A, ε_B) that are used to calculate the strain distribution by the following equations:

$$\varepsilon_{1,2} = \frac{1}{2}\left[(\varepsilon_O + \varepsilon_V) \pm \sqrt{ (\varepsilon_O - \varepsilon_V)^2 + \left[2\,\varepsilon_A - (\varepsilon_O + \varepsilon_V)\right]^2 } \right]$$

and

$$\operatorname{tg} \Phi = \frac{2 (\varepsilon_1 - \varepsilon_V)}{2\,\varepsilon_A - (\varepsilon_O + \varepsilon_V)}$$

where ε_1 and ε_2 are the secondary principal strains in the plane of measurement, Φ is the angle of rotation between ε_1 and ε_V.

The secondary principal stresses can be evaluated as follows

$$\sigma_1 = \frac{E}{1 - \nu^2} (\varepsilon_1 + \nu \varepsilon_2)$$

$$\sigma_2 = \frac{E}{1 - \nu^2} (\varepsilon_2 + \nu \varepsilon_1)$$

where E and ν are Young's modulus and Poisson's ratio of concrete.

The deformability parameters E and ν are determined by unconfined compression tests in the laboratory, performed on the same concrete cores, previously stress relieved. Alternately, the method shown in Figure 4 can be used. A pair of thin curved jacks, symmetrically placed, apply a pressure on the concrete core. Measurements of E and ν are possible from the values of strains, as the pressure is increased.

With reference to stress measurements in concrete linings, consideration is also to be given to cases when a steel reinforcement with a mesh size smaller than 10 cm is used. Due to the need to reduce considerably the overcoring diameter and the base length for strain measurements, the mechanical strain gages cannot be employed any longer. Therefore, in these cases a strain cell with electrical resistance strain gages, attached on the surface of the concrete lining, is applied as shown in Figure 5.

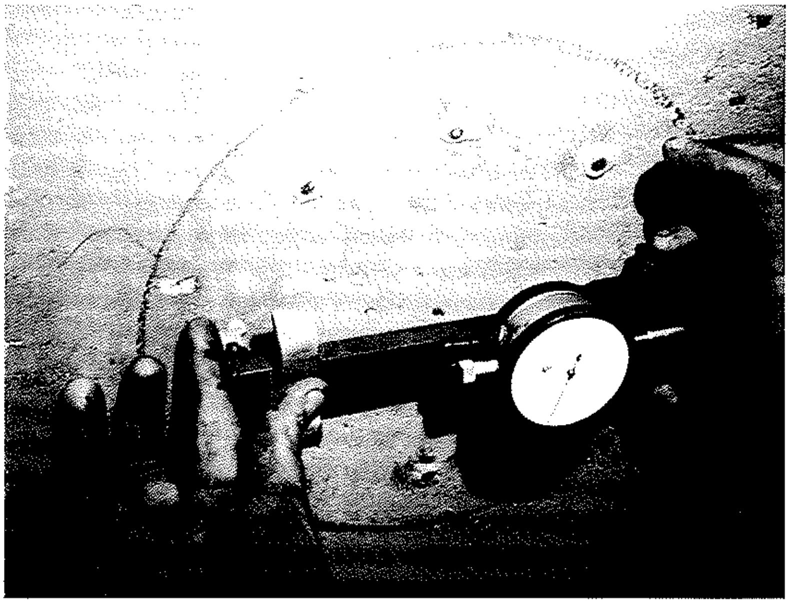

Fig. 2 Measurement of initial distance across a diameter before overcoring.

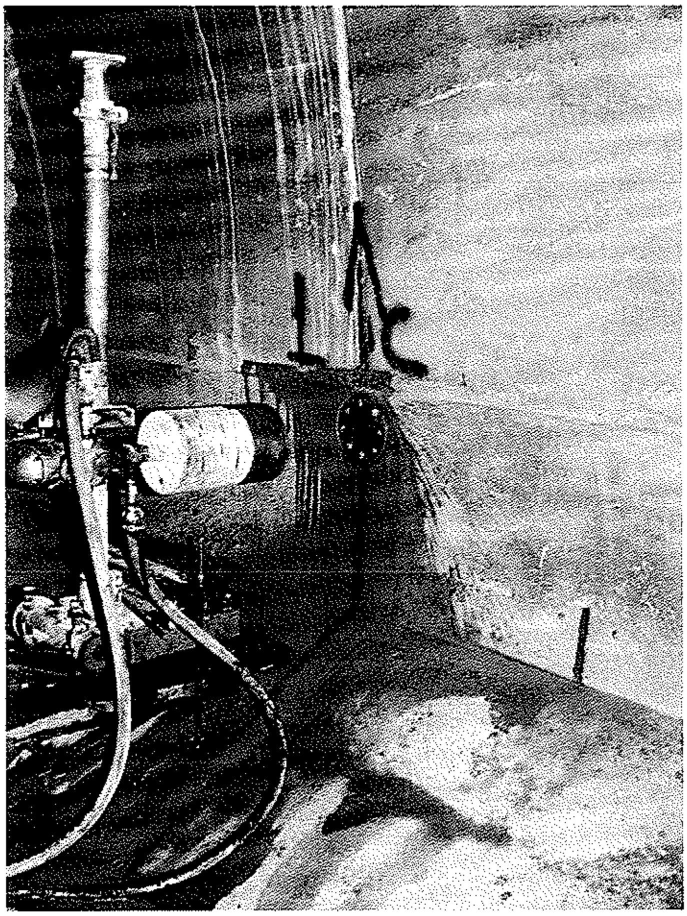

Fig. 3

Overcoring is taking place by a thin-walled bit.

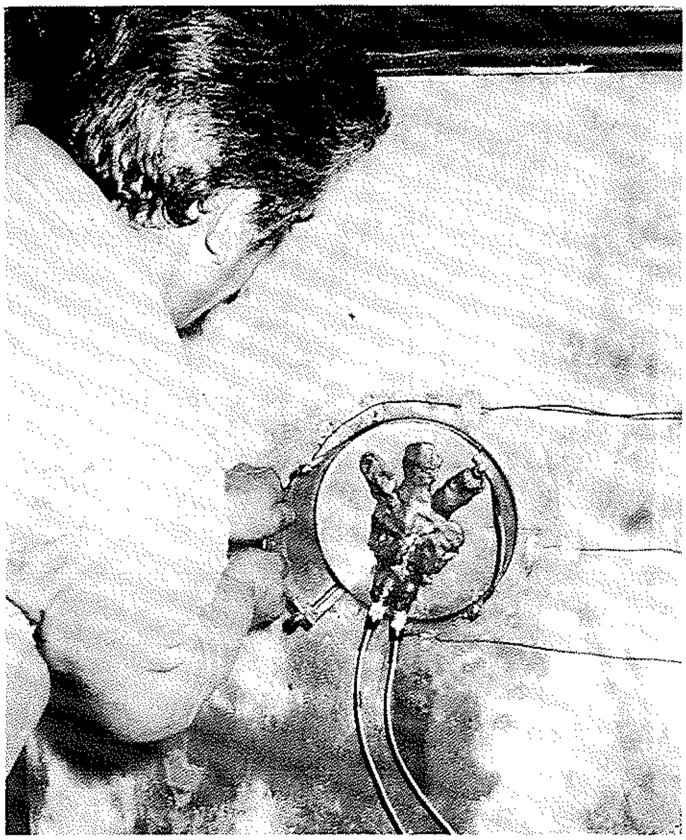

Fig. 4

Use of thin curved jacks, symmetrically placed, to determine the deformability parameters of concrete.

Fig. 5

Strain cell with four electrical resistance strain gages attached on the surface of the concrete lining. Stress relieving by overcoring has already taken place.

3. Stress measurements in brick masonry linings

For stress measurements in brick masonry linings, the flat jack method is applied as shown in Figure 6. The procedure used is briefly summarized as follows. Metal pads are cemented on the surface and the distance between each set is measured by using a mechanical strain gage (Figure 7).

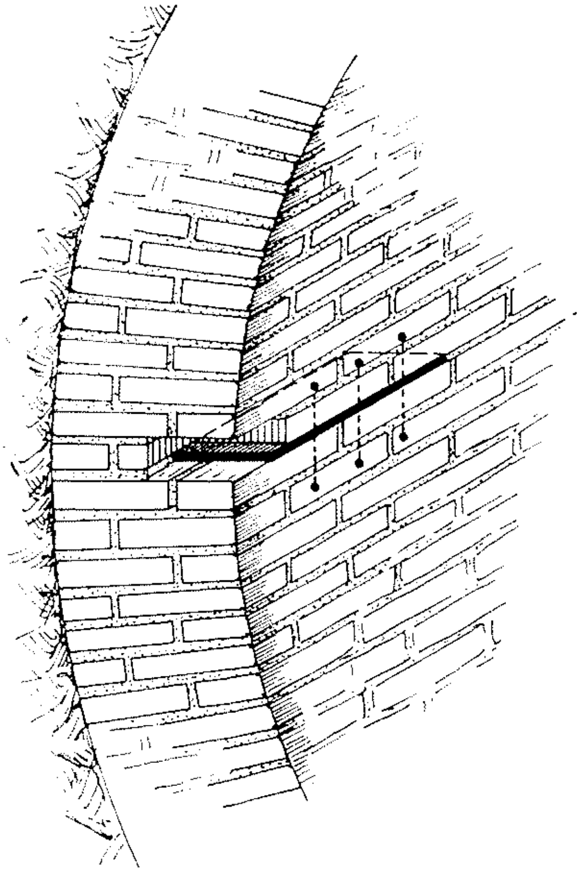

Fig. 6

Flat jack method applied for stress measurements in brick masonry linings.

Then, a slot is created by removing with care the mortar between the bricks. A stress relief taking place, the pad distances are again measured.

A thin flat jack (40x20 cm or 24x12 cm in size) is inserted into the slot and the pressure in it is increased until the distances between the pads are the same as before creating the slot (Figure 7). The cancellation pressure obtained by this procedure gives the stress acting in the lining.

By the flat jack procedure the deformability of the brick masonry lining can as well be determined. In addition to using a single flat jack, two apposite jacks may be applied and a compression test in situ is performed on a portion of the lining.

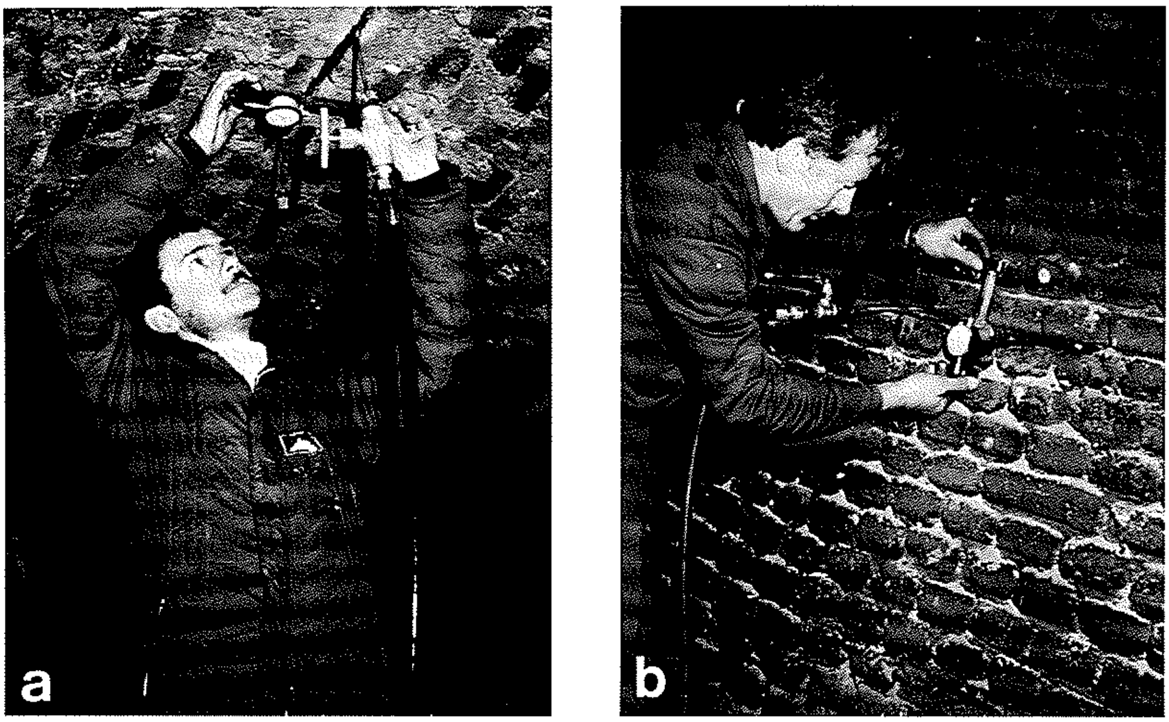

Fig. 7 Measurements of stresses in brick masonry linings by the flat jack method. (a) Test made at the roof. (b) Test made at the wall.

4. Engineering applications

In order to demonstrate the potential of the above experimental methods, two cases are briefly reported below. First, the measurements in the concrete lining of the Valsinni Tunnel (Valsinni, Italy) are described. Then, consideration is given to the use of the flat jack method in the San Pedrino Tunnel (Varese, Italy), where stresses and deformability properties in a brick masonry lining were determined.

4.1 Concrete lining

In the Valsinni Tunnel, for the sections situated in a weak rock formation (Marl) a problem was faced following the placement of the concrete lining and before invert arch installation. At the roof of a 90 cm thick lining, local failures took place as convergences occurred at the bottom, which could not be prevented. In cases, also local failures developed at the walls.

In order to decide upon the repair measures to be taken and evaluating the state of stress in the lining, the stress relief method was applied. Measurements were carried out in three cross sections with observation points at the roof and walls. In four other sections only measurements at the roof were performed (Figure 8).

The measurement sections were chosen with consideration being given to both the proximity to sections, where local failures took place, and to the values of convergences experienced at the bottom of the tunnel. The secondary principal stresses, as measured at different points along the tunnel axis are depicted in Figure 8.

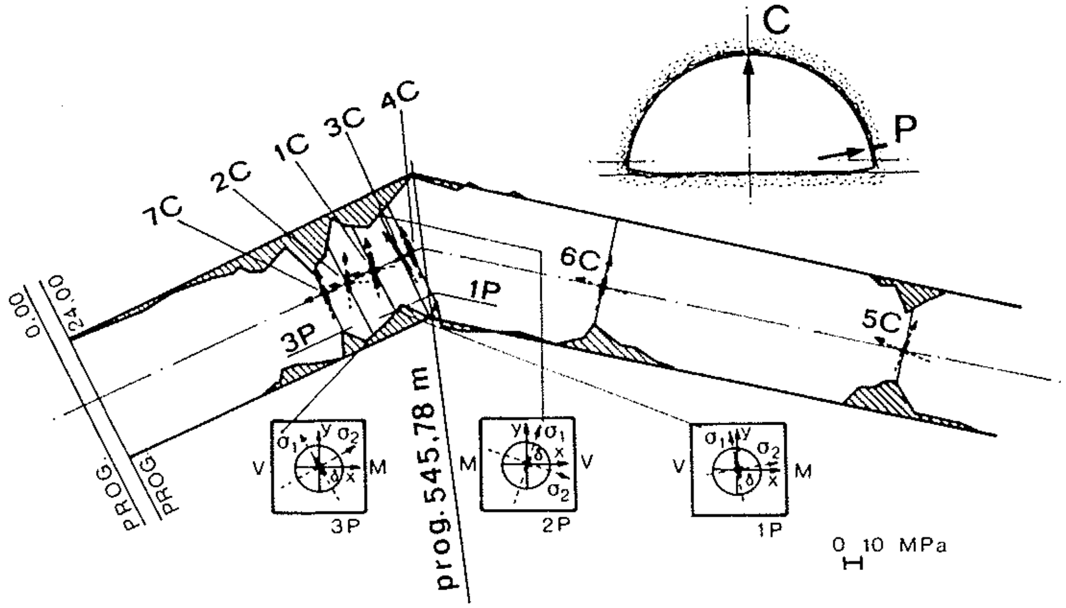

Fig. 8 Valsinni Tunnel.
Cross sections where measurements were carried out along the tunnel axis. Principal stresses in the concrete lining. Also shown are the convergences, as occurred before invert arch installation.

On the basis of the results obtained by the stress relief method, the cross sections with unacceptable values for the hoop stresses in the lining at the roof could be ascertained. These sections were found to be located near the zones where the most extensive failures occurred in the lining.

In addition to repair measures such as: (1) substitution of limited portions of the lining where failures took place; (2) use of low pressure grouting behind the lining, the problem to relieve the undesired roof compressive stresses was to be faced. It was decided: (3) to install prestressed bolts at the walls; (4) to make a cut (35 cm deep and 40 m in length) by a large diameter saw, at the roof.

In order to evaluate the effectiveness of measures such as (3) and (4), numerical modeling by the Finite Element Method (FEM) was used, prior to execution. Subsequently, the stress relief method was again applied to measure the state of

stress in the lining.
A comparison of the maximum principal stress distribution as predicted by FEM, before (A) and following (B) the cut, is illustrated in Figure 9. The results of measurements by the stress relief method carried out before (A) and following (B) the cut, are depicted in Figure 10.

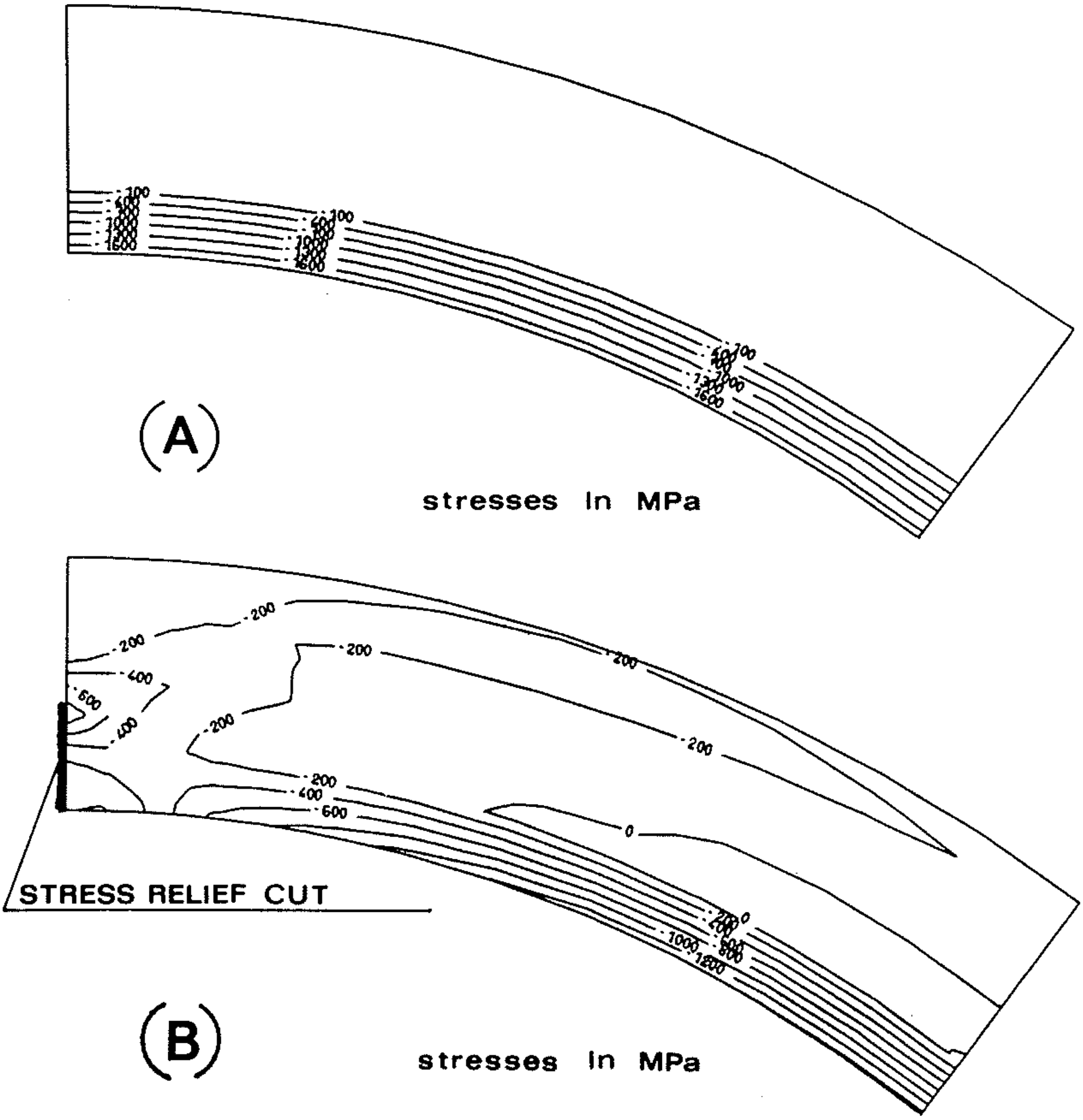

Fig. 9 Valsinni Tunnel.
Comparison of maximum principal stress distribution in the lining. (A) Before and (B) Following stress relieving at the roof. Prediction by the Finite Element Method.

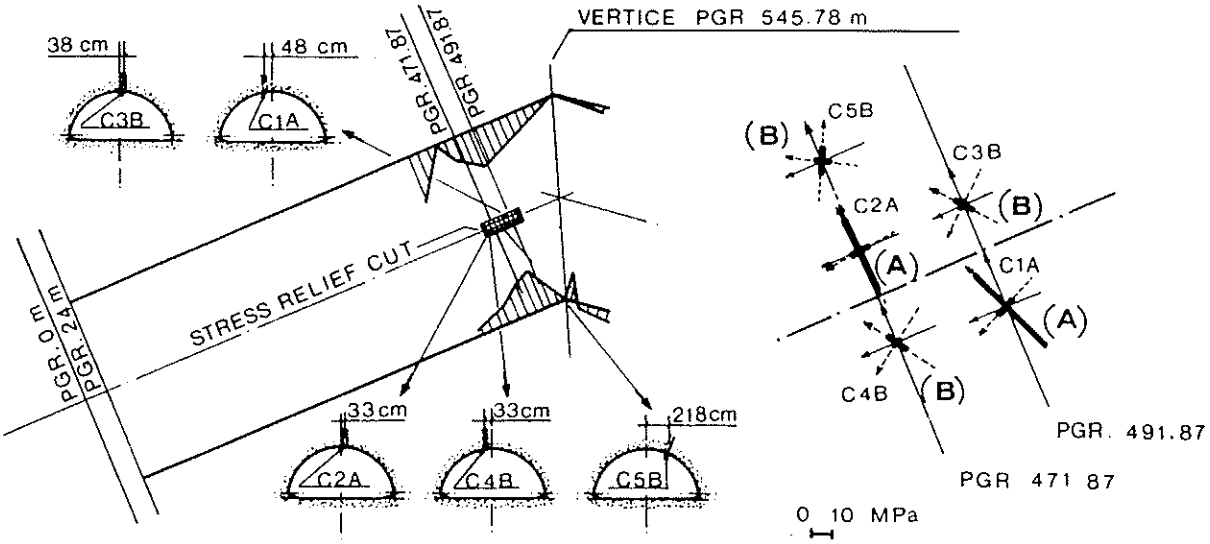

Fig. 10 Valsinni Tunnel.
Comparison of principal stresses in the lining. (A) Before and (B) Following stress relieving at the roof. Measurements by the stress relief method.

4.2 Brick masonry lining

In the San Pedrino Tunnel the problem was to measure the stresses in a brick masonry lining and to evaluate its deformability. The flat jack method was used. Measurements were carried in one cross section with observation points at both the walls of the tunnel. In two cross sections only one measurement at the wall was performed (Figure 11). The results for stresses are summarized in the table below.

Mesaurement cross section	Distance from entrance D (m)	Depth below surface h (m)	σ_t (MPa)	$\sigma_t / \gamma h$ (−)
1	132	25	1,20	2,4
2	132	25	1,12	2,2
3	39	10	0,80	4,0
4	85	20	1,04	2,6

σ_t = cancellation pressure at the flat jack

γ = 20 KN / m^3

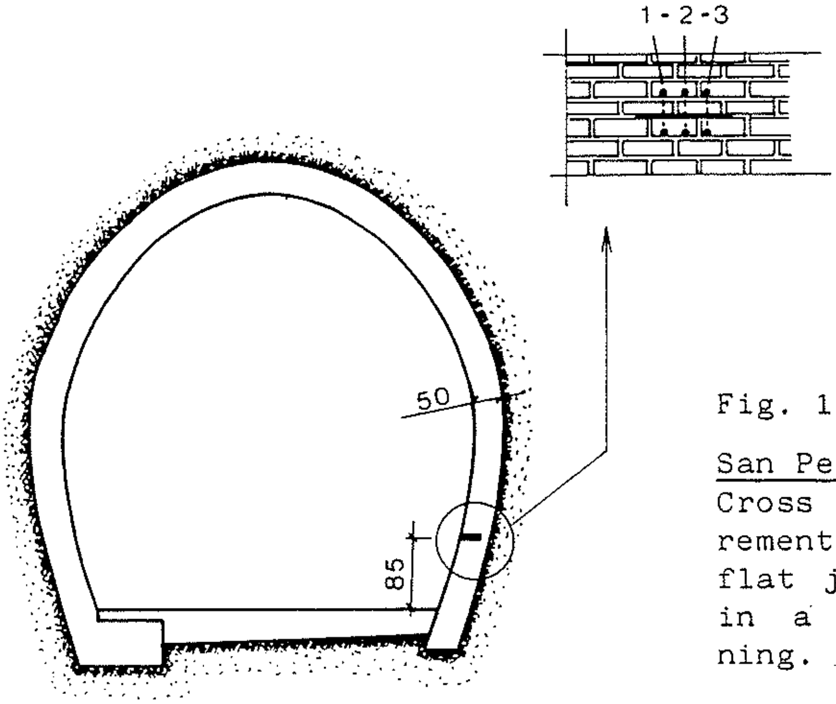

Fig. 11

San Pedrino Tunnel.
Cross section and measurement station by the flat jack method applied in a brick masonry lining.

The results for the deformation modulus E_t are depicted in Figure 12 by reporting it as a function of the stress acting in the lining. It is of interest to note that the cross section 3, where the greatest stress concentration is attai-

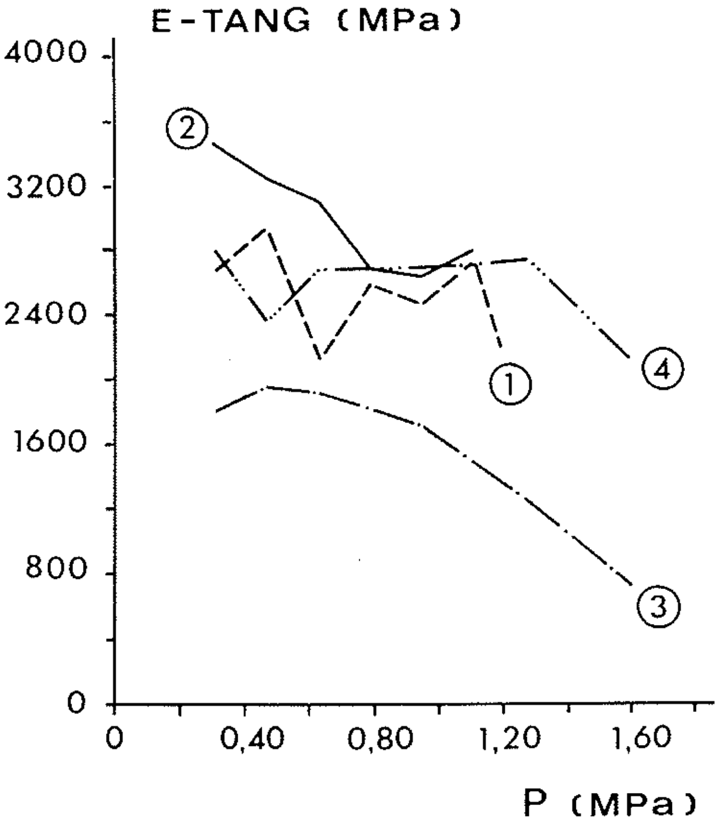

Fig. 12

San Pedrino Tunnel.
Deformation moduli for the brick masonry lining at the measurement stations 1 to 4.

ned, is also characterized by very reduced values of the deformation moduli, in consideration of the poor quality of the brick masonry lining.

5. Concluding remarks

The experimental methods reported in this paper are shown to be effective in measuring the stress distribution in tunnel linings. Either concrete or brick masonry linings can be considered. Two examples were reported taken from engineering practice.

In the first case, the stresses for different cross sections in a concrete lining were determined. The result obtained guided in the choice of the repair measures to be taken in order to give to the lining the structural integrity as required according to design.

In the second case, the measurements permitted the evaluation of the stresses acting in a brick masonry lining of a railway tunnel excavated a century ago. Also the deformability properties of the same lining could be assessed, with the advantage to ascertain the portions in the tunnel where the lining quality had decayed considerably.

6. Acknowledgements

The Authors would like to thank the following Groups for the permission to report the results of practical applications: (1) Ente per lo sviluppo dell'Irrigazione e la Trasformazione Fondiaria in Puglia e Lucania (Bari) and Impresa Lodigiani S.p.A. (Milano), for the Valsinni Tunnel; (2) Ferrovie Nord Milano and Star International S.p.A. (Milano), for the San Pedrino Tunnel; Geoanalysis s.r.l. (Torino) and I.S.M.E.S. S.p.A. (Bergamo).