Contribution to the Study of External Pressures on Tunnel Linings

Contribution à l'étude des pressions à l'extérieur des revêtements de tunnel

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SUMMARY

This paper gives the results of measurements of external pressures on a tunnel lining. The measurements were made following exceptionally high pressures which had caused great damage to the masonry lining of the tunnel. The results showed that the high pressures were caused by the low values of the angle of resistance to shear which brought about lateral squeezing causing transverse and longitudinal failures in the tunnel lining. Major lateral squeezing was noted in materials with low shear resistance ($\varphi = 27°$), however in better materials ($\varphi = 36°$) lateral pressures were not significant.

SOMMAIRE

Cet article donne les résultats des mesures de pressions à l'extérieur du revêtement d'un tunnel. Les mesures ont été obtenues suivant des pressions exceptionnellement hautes qui avaient provoqué des grands dégâts à la maçonnerie du tunnel. Les résultats ont démontré que les pressions étaient attribuables aux petites valeurs de l'angle de résistance au cisaillement, ce qui a provoqué un mouvement latéral et des ruptures du revêtement dans le sens transversal et longitudinal. On a observé des mouvements latéraux majeurs dans les sols à petite résistance au cisaillement ($\varphi = 27°$), cependant dans les sols à plus grande résistance ($\varphi = 36°$) les pressions latérales n'étaient pas significatives.

THE PROBLEM OF COMPUTING the required dimensions of tunnel walls and lining is one of great complexity because of the heterogeneity of the soil formations. This problem becomes even more complex when it is desirable that the tunnel masonry and lining should come into action at the most favourable moment during the adjustment period of the surrounding rock to the new conditions (Rabcevich, 1962; Pacher, 1963).

In the Osenik tunnel on the Sarajevo-Ploče railway line external mass pressures bearing on the tunnel lining were measured on four profile forms. The measuring was done by means of 10 to 12 flat jacks with a diameter of 0.80 m placed on and around each tunnel profile form (Fig. 1). The investigations were made in the finished part of the tunnel, when large-scale deformation and fissures appeared, although the tunnel lining was one of the heaviest of the common types (the top arch was 90 cm thick). At first the part of the tunnel involved was about 50 m in length. Over this length, but always on one side only, there first appeared numerous fissures in the upper portion of the abutment, after which the lining began to give way under pressure and threatened to cave in. The damage (the lining had been deformed inward by about 80 cm) required immediate demolition of certain rings of the old lining and their replacement with reinforced concrete.

TYPES OF ROCK UNDERLYING THE TUNNEL

In the main, two types of sedimentary rock were found which, from geologico-geomechanical point of view, were the prime factors in determining the required thickness of the tunnel lining. At the entrance of the tunnel, the sediments were of the quaternary era; along the portion near the exit and at the exit itself, lower trias deposits were present.

According to the geological interpretation of Prof. Dr. R. Jovanović, each type of sediment is uneven, non-uniform, and disturbed (particularly the lower trias). The stratification is virtually of no significance. Both types could therefore be treated as compact granular materials.

Quaternary deposits were represented by smaller calcareous boulders, gravels, sands, and loams. They were encountered in scattered layers and alternate irregular formation without any marked stratification. As shown by geomechanical examination and test data the materials were for the most part composed of larger fractions (detritus and sand), which amounted to 80 per cent. Owing to their granulometric composition these materials possess relatively high values of shearing resistance (average angle of 36°). They are basically GF materials, according to the AC classification, but their small-grained fractions (below 0.6 mm) always belong to the CL group (ijolite, kaolin group of clay materials).

Lower trias deposits were represented by three facies, the most frequent being sandstones, argillite, marlstones, thin-layered limestone, and mudstone. Some members of the series had been loosely bound but had later become—due to tectonic influence—compact granular material containing a certain percentage of clayey and loamy fractions with varying amounts of detrital material and sand.

In these deposits, although the fractions of detrital material and sand predominated in places, the fine fractions (clayey minerals of ijolite type) were so numerous that they came to lend mechanical characteristics to materials having considerably lower values.

TABLE I. LABORATORY TESTING RESULTS

Material characteristics	Tunnel—Entrance Min. values	Tunnel—Entrance Max. values	Tunnel—Entrance Average values	Tunnel—Entrance Number of tested samples	Tunnel—Exit Min. values	Tunnel—Exit Max. values	Tunnel—Exit Average values	Tunnel—Exit Number of tested samples
Natural water content, w (per cent)	16.60	5.51	9.61	32	15.85	4.07	9.71	55
Bulk density, γ (tons cu.m.)	2.462	2.047	2.240	60	24.66	2.041	2.233	76
Porosity, n (per cent)	0.296	0.111	0.209	54	0.389	0.141	0.228	75
Specific gravity, Gs (tons/cu.m.)	—	—	—	—	2.791	2.760	2.771	11
Liquid limit, w_L (per cent)	28.30	15.80	20.13	41	32.80	12.30	23.99	74
Plastic limit, w_P (per cent)	15.75	8.22	11.59	41	16.81	9.01	12.04	74
Plasticity index, I_P (per cent)	14.55	3.37	8.48	41	19.63	3.29	11.89	74
Consistency index, I_C	2.420	0.433	1.289	28	1.695	0.784	1.169	54
Shrinkage limit, w_S (per cent)	—	—	—	—	11.926	9.063	10.424	7
Shearing characteristics of undisturbed samples								
φ	—	—	—	—	27° 00′	23° 43′	25° 45′	7
c(kg/sq.cm.)	—	—	—	—	0	0	0	7
Shearing characteristics of disturbed samples								
φ	42° 00′	27° 42′	35° 38′	44	32° 37′	19° 18′	26° 46′	59
c(kg/sq.cm.)	0	0	0	44	0	0	0	59

The coarser fractions (detrital and sand) ranged from 20 to 75 per cent. The consistency index as a rule exceeded 1.0, but the material was not infrequently of a firm consistency. Under a reduction in pressure the materials tended to swell; swelling, however, proved to be rather slight under a pressure as low as 4.00 kg/sq.cm., the swelling pressure amounting to 6.00 kg/sq.cm. According to the AC classification, the materials belonged to the GF and CL-SF groups. The sieved material (0.6 mm) belonged to the SF and CL groups.

Comprehensive tests showed that the materials had low shearing resistance, the average value of their angles of resistance being 27°. Table I gives the principal data for the materials concerned.

PRESSURE DISTRIBUTION IN CROSS-SECTIONS

Pressure measurements were made on four tunnel profiles: three in the material of lower trias (rings 244/245, 239, and 233) and one in quaternary sediments (ring 164). Measurements on ring 244/245 were made after the cracked concrete lining had been replaced by a new one. The measurements were made over a period of one to one and a half years (650 days).

Unfortunately the primary stress state could not be established since the measurements coincided and interfered with construction activities. Only secondary states were actually registered, that is, in the planes normal to the axis of the tunnel. Figs. 1, 2, and 3 show the pressure distributions along the circumference of each ring as well as the changes in

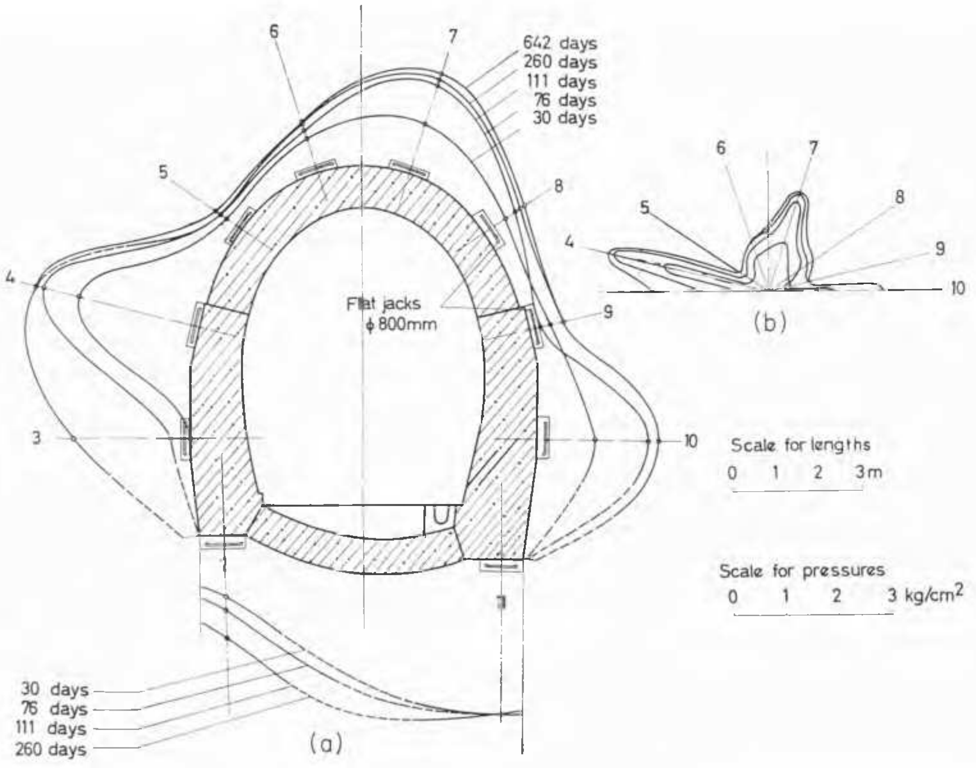


FIG. 1

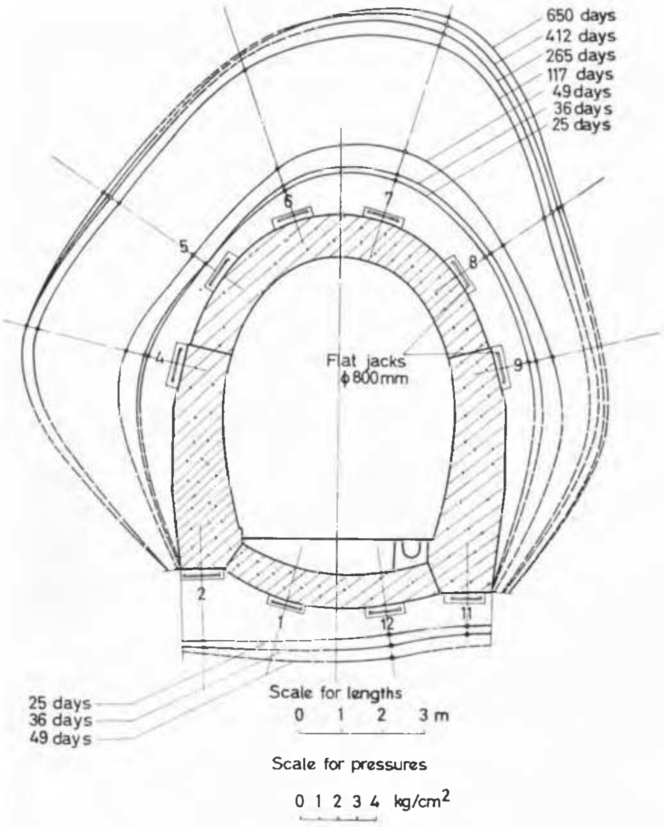


FIG. 2

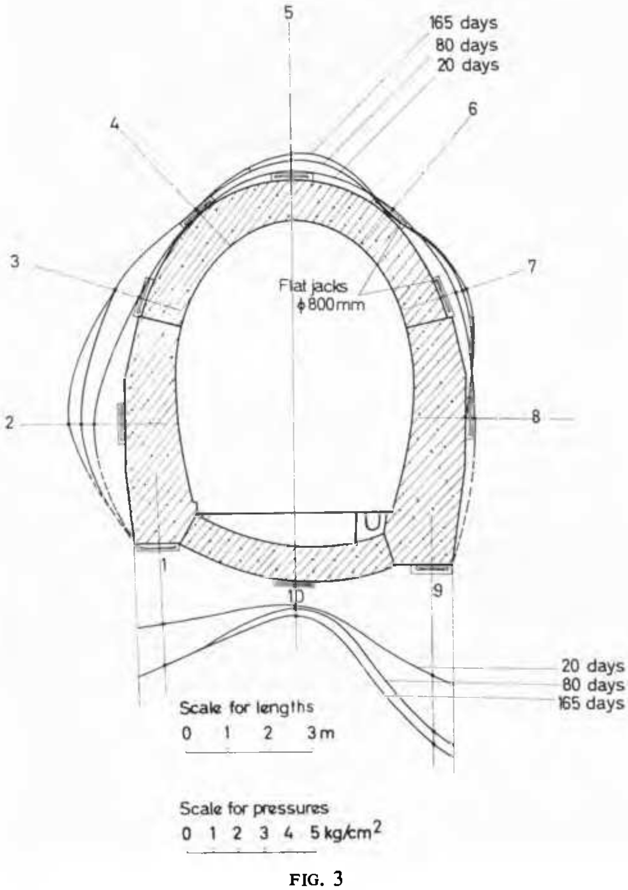


FIG. 3

relation to time. Fig. 4 shows rates of increase in pressure upon each of the profiles in relation to time and the progress of the work.

INCREASE OF PRESSURES PER UNIT TIME

Once the shape of the tunnel profile has been adopted, the magnitude and the time increase of pressures depend primarily on the type of material, the method of work, and the length of time required for the completion of a ring (excavation, timbering, and lining). All these factors made their influence felt to the full extent during the working operations in the part of the tunnel that ran through the triassic deposits.

Since alteration of the shape of the tunnel and change of the method of work would not be economical, it was decided to effect the necessary stability by reinforcing the tunnel masonry and lining, by a further application of Kuntz's method of excavation, and, by making, at the same time, changes in working methods. In point of fact, the measures adopted were only partially successful, as the necessary stability was achieved mainly through a reinforcement of the lining, and only partly owing to a diminution of pressures due to more suitable methods of work.

After the appearance of fissures in the linings of a series of rings, pressure gauges were installed in ring 239 and the work continued with, however, a greatly reduced working length since two rings at a time, 4 m long were used (Fig. 4).

With the adopted method of excavation and the actual reduced rate of progress caused by the nature of the material, disturbances of mountain rock on a larger scale could not be prevented, so that material occasionally poured into the excavated profile of the tunnel.

While the work was proceeding in this manner, pressures continued to increase for about three to four months, and then continued to do so at a slower rate for more than 650 days (Fig. 4). It is remarkable that a considerable increase in pressures was noted each time the successive rings were about to be excavated. Likewise, stabilization of pressures at low values on ring 239 was observed to last until the excavation of other rings began.

The same phenomena were observed during the taking of measurements of the ring 233. The measurements showed that pressure on a reconditioned or newly built ring was considerably less, so that even after 600 days the pressures on the ring were nowhere near those of rings 239 and 233.

As for the ring in quaternary sediments, the period of pressure increase was somewhat shorter. The data obtained after about one year indicated that the pressures would not increase further. After thirty days of measurements, the pressures in these materials were considerably lower. Consequently, no limitations were set as to the method by which work was being done, and construction could proceed over a much greater length. The thickness of concrete lining was also reduced shortly after, on the basis of these measurements and geotechnical examination and tests.

AN ANALYSIS OF THE PHENOMENA

Pressure distribution about the tunnel masonry and lining differs in regard to intensity and the direction in which maximum pressures occur, depending on whether construction takes place in quaternary or triassic materials. Whereas the quaternary pressures are low and, in the area of the crown, mainly oriented symmetrically to the vertical, those of lower trias tend to be considerably higher, the axes of maximum pressures making angles of about 20° and 110°

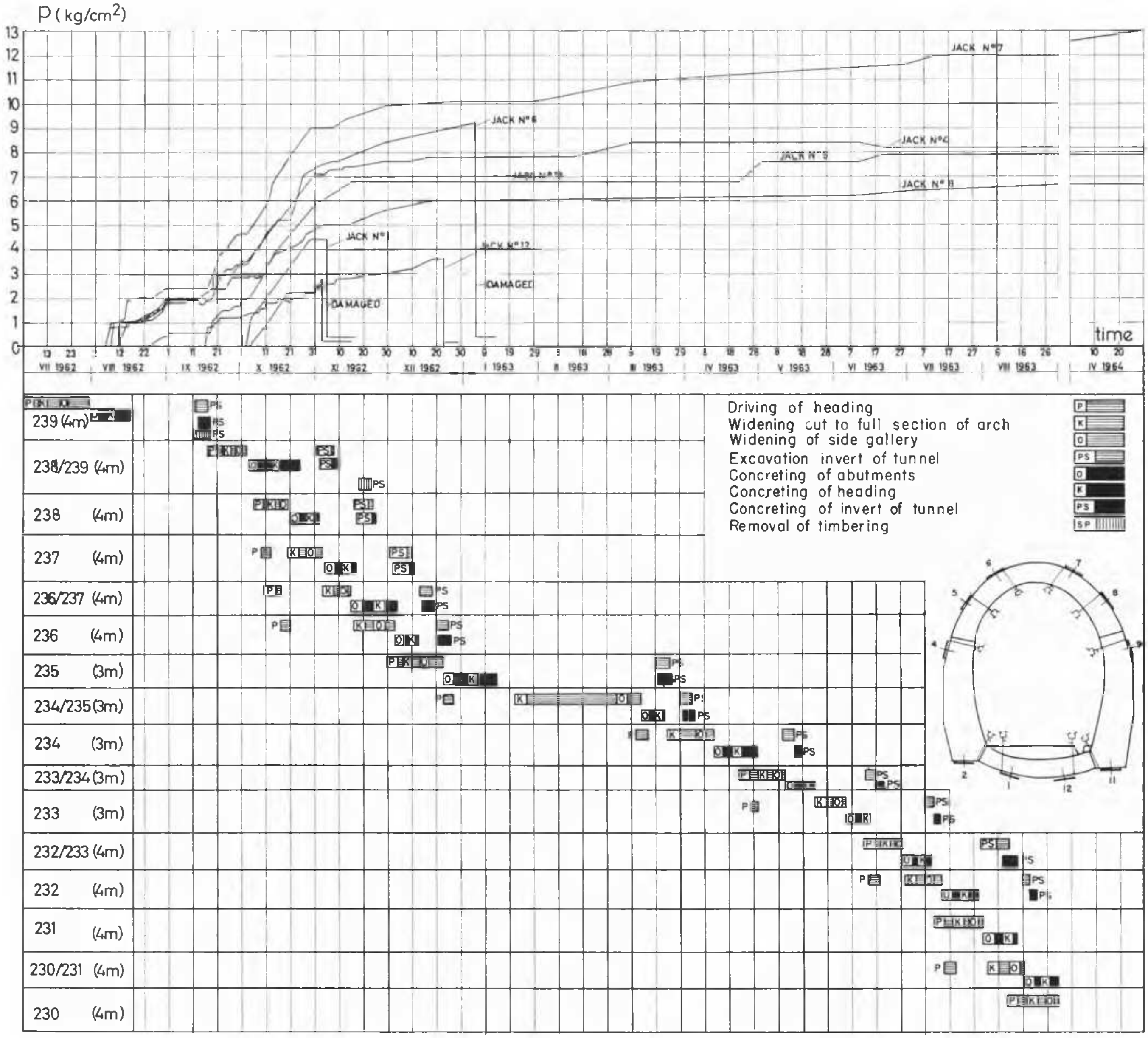


FIG. 4

respectively with the vertical. In other directions the pressures are as a rule lower. A certain symmetry of pressures in the upper portion of the tunnel can be said to exist in relation to the line making an angle of about 20° to the vertical.

The causes of these phenomena are to be sought mainly in the inferior shearing characteristics of the material, in the primary strain state of the mountain rocks, and in the manner in which construction is carried out.

Large side pressures are caused by low values of shearing resistance, which in turn bring about a widening of the static tunnel opening (Rabcevich, 1962, Fig. 5b). An increase in the static width of the tunnel also causes the active arch to rise correspondingly, which in turn causes an increase in vertical pressures. In fact, each of the three profiles bore distinct marks of the effects of lateral squeezing of the material, and the directions of the pressures were on the whole normally oriented, the angle made with the vertical being 20°. It was this effect that was mainly responsible for the obtained shape of pressure distributions, even when lateral pressures proved to be at a maximum.

The influence of the size of the angle of shearing resistance may be approximately analyzed (Fig. 5a). Assuming the tunnel to be approximately circular, the relationships may be found, for different stress states defined by the relation N, between horizontal and vertical normal stresses in a horizontal plane drawn through the point A, dependent on the relation r/a (Terzaghi and Richart, 1952). On the other hand, the limiting value of the relationship of these normal stresses is given by the formula,

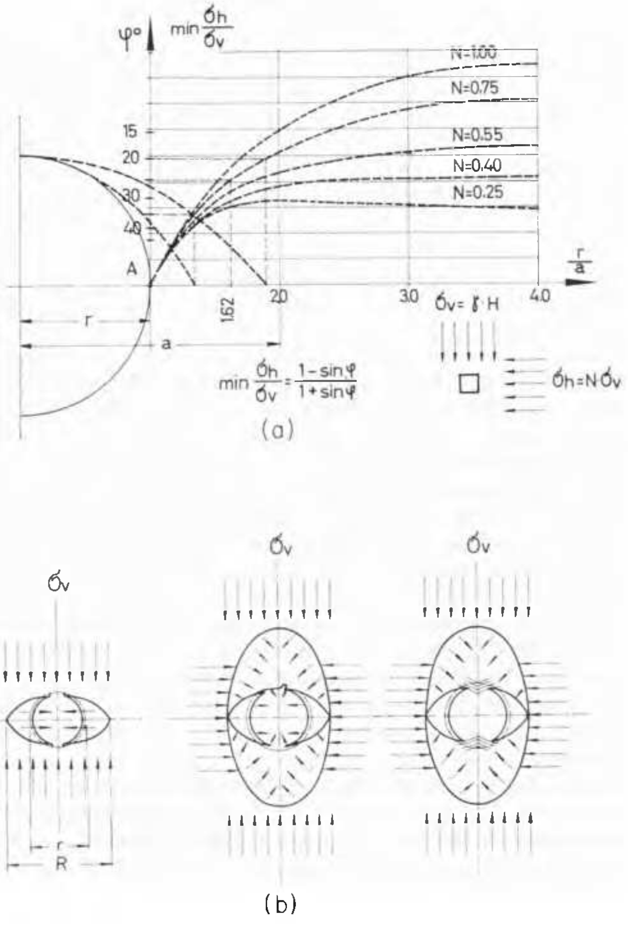
$$\min(\sigma_h/\sigma_v) = (1 - \sin\varphi)/(1 + \sin\varphi),$$

which makes it possible to determine, for the given angle, φ, the relation r/a, which is the maximum value for lateral squeezing.

Assuming, on the basis of pressure distribution on the ring 239, $N = 0.75$ (which is near the actual figure) and $\phi = 25°$, we obtained for the actual increase of the static width of the tunnel a value 62 per cent greater than its actual width. For $N = 0.55$ the percentage would amount to about 85 per cent. For $\phi = 36°$, where quaternary material is concerned, the increase would amount to about 30 per cent and 38 per cent in the first and the second cases, respectively.

However, as well as the effects of lateral pressures and the emergence of relieving arches in the cross-section, formation of relieving arches in longitudinal direction also occurred in the triassic material. Although the working length was reduced to the minimum (two rings of 4.0 m each), a major increase of pressure invariably occurred at the start of excavation of every successive ring until the stagnation stage of pressures was reached owing to the progress of operations. The occurrence of relatively low pressure in the case of ring 233 can be explained by greater shearing resistance in subsequent rings, or by the presence of large groupings of firm rock in the immediate neighbourhood, evident from certain profiles.

The method adopted for the reconditioning of profiles is evidently not to be recommended in the case of materials with low shearing resistance. The method proved suitable and effective for the work done at the entrance of the tunnel, but less so at its exit. The adopted method of reconditioning requires the fashioning of props and struts, which would hardly be feasible in view of the nature of triassic materials.



(a)

(b)

FIG. 5

Owing to the damage done to the measuring instruments placed in the lower portions of the rings, no clear picture could be obtained of the increase in pressures on the bottom arches of some rings. Nevertheless, the pressure diagrams for rings 164 and 233 give a very logical picture of pressure distribution and the function of the bottom arch.

All measurements were taken during construction operations, causing many difficulties and much damage to the measuring instruments. All the same, the measurements gave us some very useful data about location, quantity, and incidence of mountain pressures. Preliminary examination of the most important mechanical properties of the material proved most useful since the data obtained were invaluable for computing the dimensions of the tunnel lining and allowed substantial economies in building materials.

It has been shown that preliminary measurement and technical research with materials of this and other similar types invariably results in the lowering of costs of tunnelling and tunnel building under difficult conditions. The method therefore deserves to be more widely used.

CONCLUSIONS

1. Where plastic, loosely bound, and greatly dislocated and damaged rocks are concerned, relieving arches of great extent are formed, running both transversely and longitudinally, if the material through which the tunnelling proceeds is one with relatively low shearing resistance. Formation of such arches leads to high pressures both laterally and vertically. Lateral pressures can at times be higher than the vertical ones. As shown in the case referred to, these effects—with consequent difficulties—tend to arise when the angle of shearing resistance is about 27°; they are at a minimum at an angle of approximately 36°.
2. In cases where the above phenomena are liable to occur, the conventional methods of computing the dimensions of tunnel masonry and lining are not suitable and a preliminary examination and tests have to be made. The choice of the method of work and construction of tunnel profiles should only be made after and on the basis of preliminary research work. Examination of material both prior to and parallel with the execution of works has proved most useful.
3. The process by which a mountain mass, with rocks similar to those described herein, adjusts to changed conditions around the tunnel is very slow. In our case the more important changes will be taking place for a period of about two years.
4. With reference to the bottom arches, great differences were noted in the distribution and manner of action of pressures between materials with low and higher shearing resistance respectively. Special attention should be paid therefore to assessing the right moment for and the manner of the construction of the bottom arches.

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