Stress fracturing around a deep-level bored tunnel

by T. R. STACEY*, Pr. Eng., D.Sc. (Eng.), D.I.C. (Member) and
C. L. de JONGH†, B.Sc. (Member)

SYNOPSIS

Fracturing of the rock caused considerable difficulties during the boring of a deep-level tunnel in hard rock. A pilot bore was suggested as a possible means of reducing the effect of the fracturing, and this possibility was investigated theoretically by means of a three-dimensional elastic stress analysis. Failure criteria were applied to the results of this analysis, and it was found that fractures predicted by the use of a simple criterion of limiting tensile macro-strain criterion agreed remarkably well with *in situ* observation. It was concluded that fracture could not be avoided and that a pilot bore was likely to aggravate tunnelling conditions.

SAMEVATTING

Swigting het aansienlike probleme teweeggebring by die boor van 'n diep geleë tonnel in harde rots. 'n Voorboor was voorgestel as 'n moontlike metode om die swigtingseffek te verminder. Hierdie metode is derhalwe teoreties ondersoek d.m.v. 'n drie dimensionele elastiese syfer ontleding. Die teoreties bepaalde spannings is in 'n aantal swigtingkriteria vervang en dit is bevind dat die *in situ* waargenome gedrag opmerklik goed deur 'n eenvoudige makro-uitsettings vervormings-kriterium voorspel kan word. Daar is ook tot die gevolgtrekking gekom dat swigting nie vermy kan word nie en dat 'n voorboor waarskynlik booromstandighede verder sal verswak.

Introduction

A hard-rock tunnel-boring machine was commissioned recently at a gold mine on the West Rand in South Africa. The machine bores a tunnel of 3,36 m diameter and is intended for haulage development work, its first task being to bore a footwall drive in quartzite at a depth of over 2000 m. This boring site is far removed from any stoping activity. Soon after the boring operations had started, the machine encountered problems that severely curtailed its progress. These problems were as follows:

(i) spalling of rock from the sidewalls, which in some cases was so extensive that the machine grippers could not reach the sidewalls;
(ii) fall-out of blocks of rock from the face;
(iii) abnormally high cutter wear, which resulted from inadequate gripping owing to fracturing of the sidewalls;
(iv) damage to the belt conveyor caused by sharp pieces of fractured rock;
(v) accumulation alongside the machine of rock debris, which was hand-lashed and resulted in delays.

It is obvious that these problems can be ascribed to rock fracture, though conditions were aggravated by two very well-defined bedding planes in the quartzite, which cut across the tunnel. It was believed that the fracturing resulted from high field stress in conjunction with the stress-raising effects of the tunnel. In particular, a high stress concentration factor was expected at the re-entrant angle around the perimeter of the bored face.

A solution envisaged for the problem[1] was the use of a pilot bore, the aim being to simulate a smooth curved boring head as shown in Fig. 1. This, it was hoped, would reduce the fracturing and result in fracture orientations that were less detrimental for boring. Theoretical stress analyses[2] were therefore undertaken so that the diameter and length of the pilot bore could be optimized.

*Steffen, Robertson and Kirsten Inc., Consulting Geotechnical Engineers, Johannesburg.
†Goldfields of South Africa Ltd, Johannesburg.

Theoretical Model

The bored tunnel is horizontal, and, since the vertical field stress is greater than the horizontal field stress, the problem is fully three-dimensional. Of several possible methods of stress analysis, the three-dimensional surface-element method[3] developed by the Chamber of Mines Research Laboratories was chosen. In this method, the shape of the excavation is represented by two-dimensional surface elements.

The model adopted for analysis is shown in Fig. 2. The length of the tunnel was chosen as ten times its diameter in the belief that this length would be sufficient to prevent the interaction of end effects. The slightly curved face produced by the borer was not modelled accurately, a simple flat face with a sharp angle at its perimeter being used instead.

The field stresses assumed for the analyses were

$\sigma_x = -35,0$ MPa
$\sigma_y = -17,5$ MPa
$\sigma_z = -52,6$ MPa.

The directions of the axes are defined in Fig. 2. The following material properties were used in all the analyses:

Modulus of elasticity	75 GPa
Poisson's ratio	0,25
Uniaxial compressive strength	172 MPa
Angle of internal friction	45°.

Subsequent tests on cores removed from the tunnel borer site showed an average uniaxial compressive strength of 230 MPa.

Analysis of Rock Fracture

The method of stress analysis used in this investigation is based on the assumption that the rock mass behaves as an ideal elastic isotropic homogeneous medium. The rock-fracturing aspect was investigated by comparison of the elastically determined stresses with two fracture criteria, the aim being to determine the possible extent of fracturing and the orientation of potential fracture planes.

The first fracture criterion was derived directly from

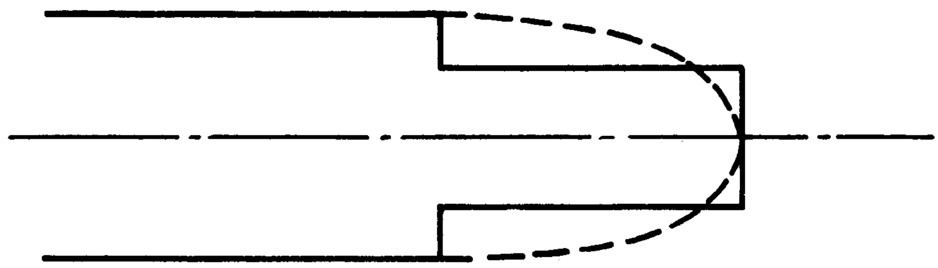

Fig. 1—Use of a pilot bore

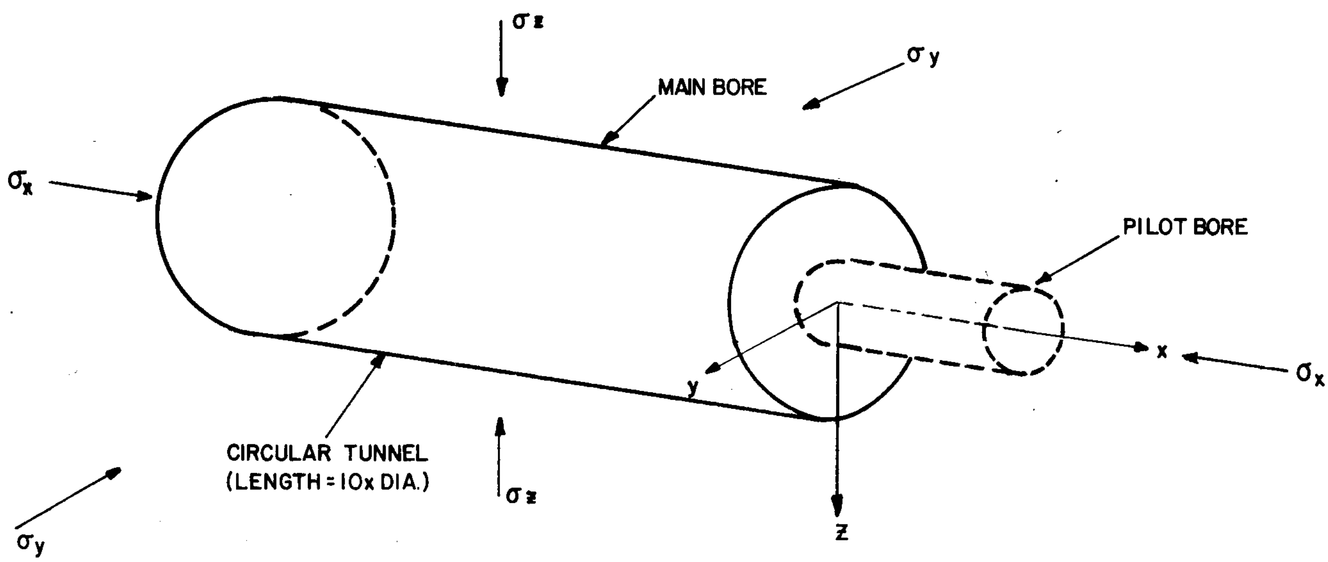

Fig. 2—Idealized 'wedge-shaped' drag bit

the Mohr stress circle. This defines a shear fracture due to failure in a triaxial stress state and provides the orientations of potential shear fracture planes.

The second failure criterion resulted from a discussion with Wagner[4] centering on the observation that rock splits parallel to the direction of maximum compression[5], i.e., perpendicular to the direction of the maximum tensile strain. This is termed axial cleavage fracturing by Gramberg[6] and is, in fact, an indirect tensile fracture. Both Fairhurst and Cook[5] and Gramberg[6] make use of a *stress* approach, adapting the Griffith theory to explain the mode of fracturing. However, in the present application a macro-*strain* approach was employed. The criterion adopted can be stated simply as follows: fracture of the rock will occur in indirect tension when the tensile strain exceeds a limiting value, which is dependent on the properties of the rock. This approach allows for the fact that, even though all three principal stresses may be compressive, the triaxial state of stress can result in a tensile strain. The 'most tensile' principal strain will correspond to the least compressive principal stress. The orientation of the potential fracture plane will correspond to the minor principal plane, i.e., it will be normal to the direction of the minor principal stress.

Results

The first and most obvious observation that could be made from the results of the stress analysis is that the stress levels around the tunnel face were lower than had been anticipated. In particular, the expected high stress concentration around the sharp re-entrant angle at the perimeter of the tunnel face was absent. The stress concentrations around the tunnel end were low owing to the supporting effect of the tunnel face. This was confirmed by the work of Galle[7] as reported by Van Heerden[8]. Galle investigated the stress concentration around a flat borehole end by means of a three-dimensional photo-elastic model. For that model subjected to a uniaxial stress field, the maximum stress concentration factor was 2,8. This is less than the value of 3,0 that would apply on the wall of the hole some distance back from the end. Moreover, in a non-uniaxial stress field the stress concentration factor is likely to be even lower. In the present analyses, in fact, the maximum stress concentration calculated at a point 0,03D (where D is tunnel diameter) from the corner was 1,67. It therefore became apparent that the highest stresses would occur on the tunnel sidewalls some distance *behind* the face, and that the rock fractures observed underground were not due to a high stress concentration at the sharp angle.

Tunnel Without a Pilot Bore

From the failure criterion based on the Mohr circle, it was found that no failure should occur if the uniaxial compressive strength used is obtained in laboratory

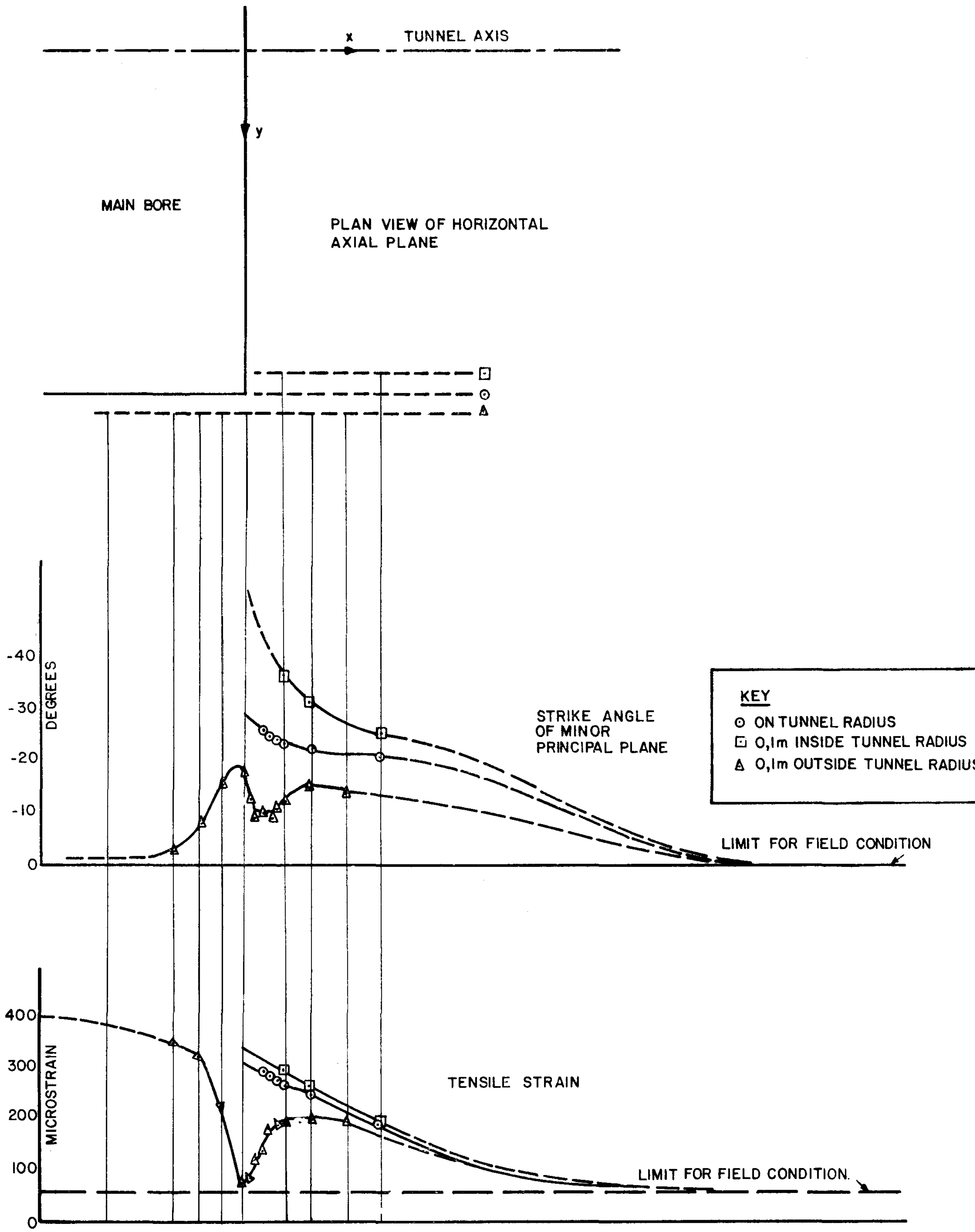

Fig. 3—Tunnel without pilot bore: results on horizontal axial plane

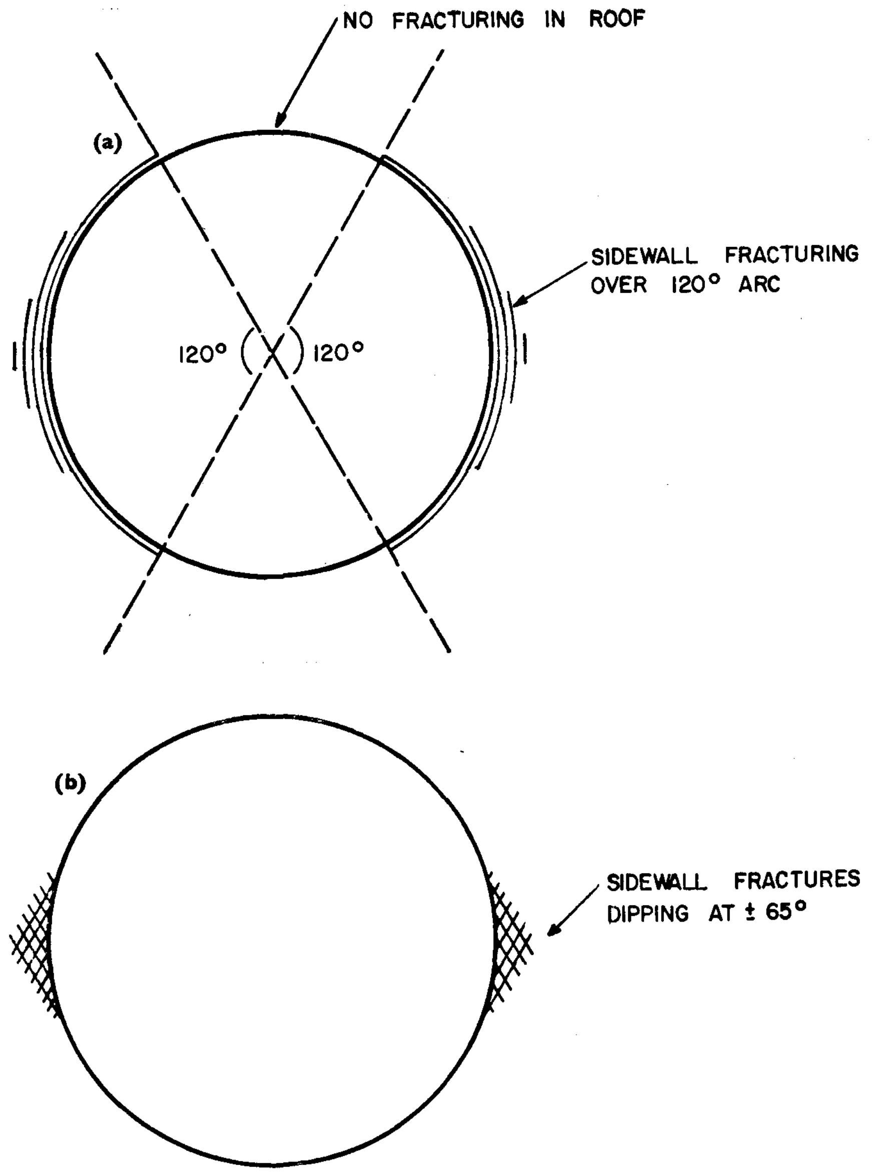

Fig. 4—Diagrammatic representation of sidewall fracturing
(a) Fractures predicted by the criterion of limiting tensile strain
(b) Fractures predicted by the criterion based on the Mohr circle

tests on quartzite specimens. In an attempt to explain the fracturing around the tunnel, it was assumed that the strength of the rock mass was one-quarter that of the specimen. Even on this extreme assumption, possible failure was limited to a zone on the horizontal axial plane ahead of the face but inside the radius of the tunnel. Since this zone was to be cut by the boring machine, it was of little consequence.

It was concluded from these results that the shear failure criterion could not describe the real situation.

When the second criterion (limiting tensile strain) was applied, it was found that the largest values of tensile principal strain occurred in the horizontal axial plane, and consequently attention was focused on that area. Fig. 3 shows graphs of the tensile strains near the 'corner' of the tunnel.

In the application of the failure criterion, the limiting value of tensile strain was taken to be 0,0002. This represented a reduction of less than 3 to 1 on the tensile strain of the laboratory specimen at the point of failure. With this critical strain value, it can be seen that failure was possible up to 0,6 m ahead of the tunnel face at a radius equal to that of the tunnel (Fig. 4). The area of potential fracturing was restricted to a zone close to the horizontal plane of the tunnel. Behind the tunnel face the zone of potential failure became much larger, extending over an arc of about 120°. The calculated depth of these fracture zones into the sidewalls appeared to be limited to about 0,2 m at midplane level. The depth appeared to be less above and below the midplane.

The orientations of the fracture planes predicted by the limiting tensile strain criterion were also calculated. The strikes of these planes in the sidewalls at axis level are also plotted in Fig. 3. The dip of the planes at this level was in all cases approximately vertical. Based on the limiting strain value of 0,0002, the results in Fig. 3

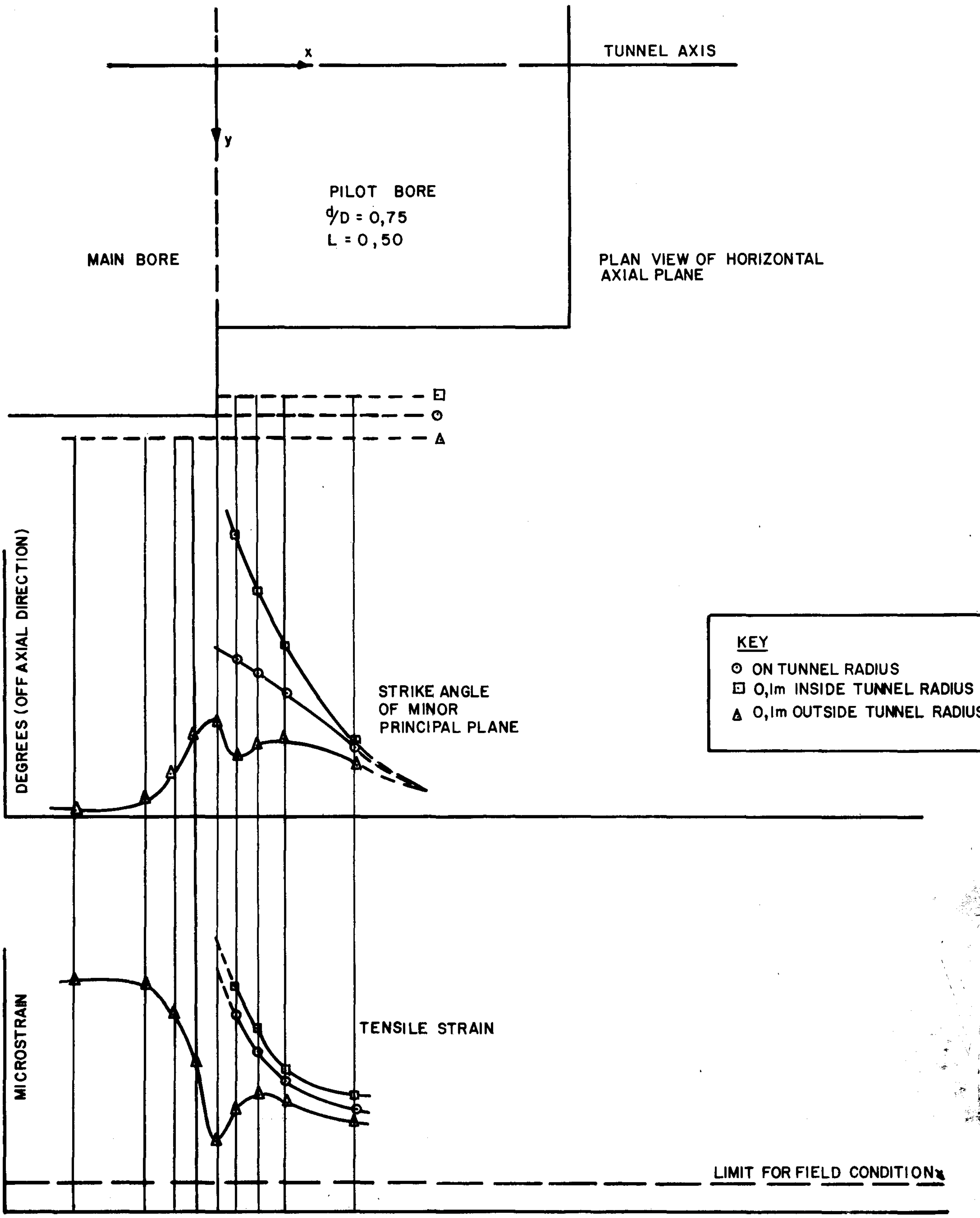

Fig. 5—Tunnel with pilot bore: results on horizontal axial plane

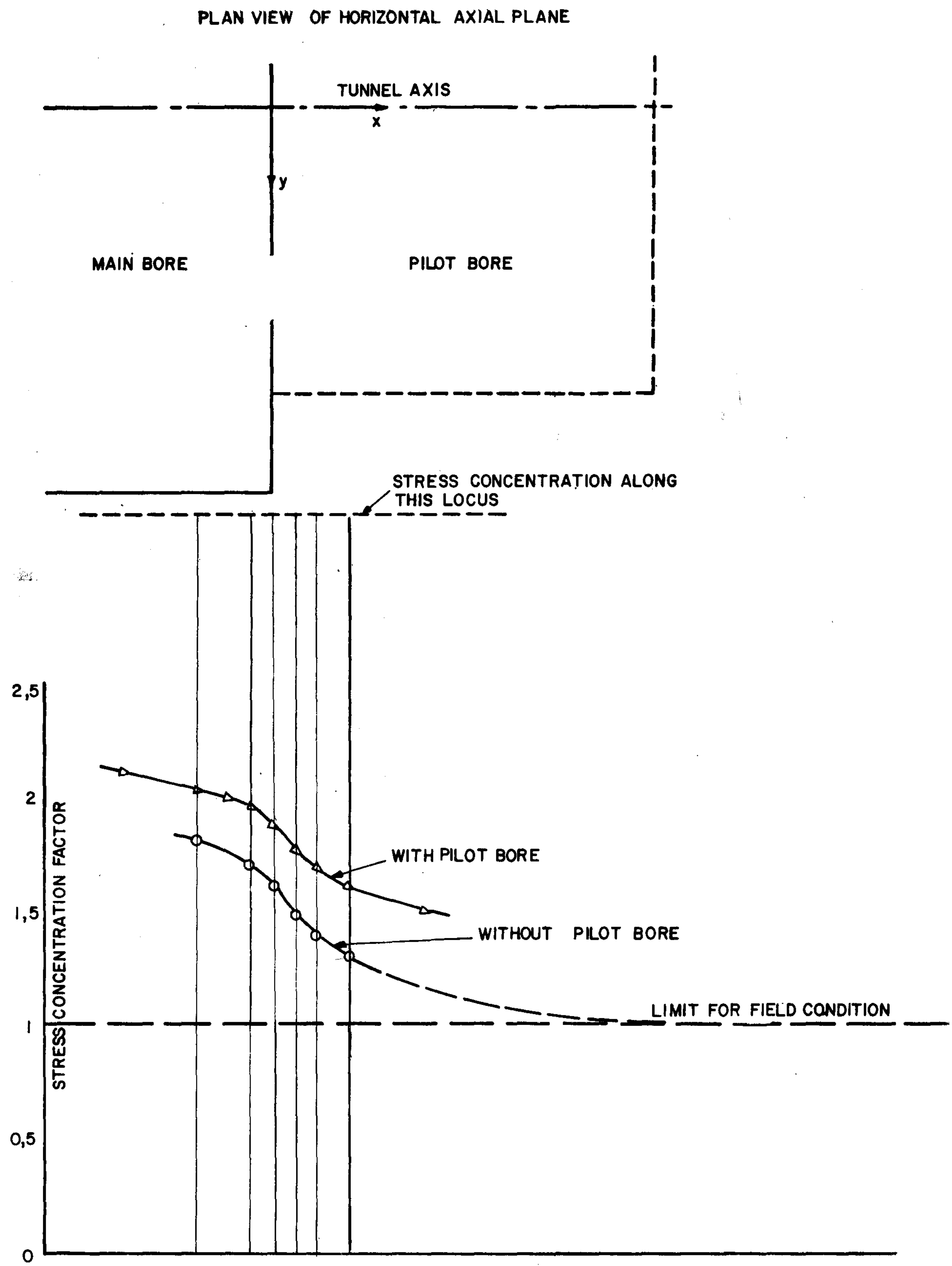

Fig. 6—Concentration of vertical stress on horizontal axial plane

show that fractures would initiate in the sidewalls on the (future) tunnel radius at an inclination of about 20° to the tunnel axis, i.e., these would be the fracture orientations observed after the tunnel had been cut. Ahead of the face and within the tunnel radius, the strike of the fracture planes was much greater, indicating that the planes would follow the corner of the tunnel to become parallel to the tunnel face.

Behind the face, i.e., where the fracture zone was enlarged, dips of the minor principal planes were approximately tangential to the tunnel bore. The predicted form of the fracture zones is shown diagrammatically in Fig. 4(a). Strike directions, as shown in Fig. 3, were almost parallel to the tunnel axis, indicating that, if failure were to initiate only behind the face, fracture planes would probably not be visible since they would be approximately concentric with the tunnel surface. The criterion based on the Mohr circle also predicted strike directions almost parallel to the axis of the tunnel. However, the indicated dip directions were about 65°, indicating that longitudinal fracture traces should be observed in the tunnel. The possible shear fractures are shown in Fig. 4(b) and should not be confused with the indirect tensile fractures detailed in Fig. 4(a).

The stress analysis indicated that the roof of the tunnel over an arc of about 60° was in a low stress environment. Rock fracturing in this zone would therefore be unlikely.

The possible merits arising from the use of pilot bores were evaluated from stress analyses for tunnels with pilot bores of length 0,5*D* and 0,75*D*, where *D* is the diameter of the tunnel. Fig. 5 shows the distribution and magnitude of the tensile strains in a form directly comparable with Fig. 3. It can be seen that the tensile strains were greater than those without a pilot bore. Similarly, the stress concentrations at corresponding positions on the sidewalls were also greater (Fig. 6). As could be expected from the higher stresses, failure as predicted by the shear stress criterion would be more widespread. Again, however, the only failure ahead of the main bore as predicted by this criterion would be inside the radius of the tunnel.

Discussion

The results of the stress analysis indicate that, even if aspects of rock failure are neglected, the tunnel with a pilot bore is less favourable than that without. This was unexpected since the programme of investigation originally formulated was based on the assumption that a pilot bore would improve the situation at the face of the tunnel. However, the programme assumed that the right-angled corner at the face was a zone of high stress concentration, and this was subsequently found to be incorrect. The stress analysis clearly shows that the tunnel face shields the tunnel walls from the effects of the ground stresses, and that this shielding effect diminishes with distance from the tunnel face. Therefore, it is to be expected that, at a given distance behind the full-size tunnel face, the situation will worsen with an increase in the diameter of the pilot bore. Consequently, the aim of the theoretical analyses, which was to deter-

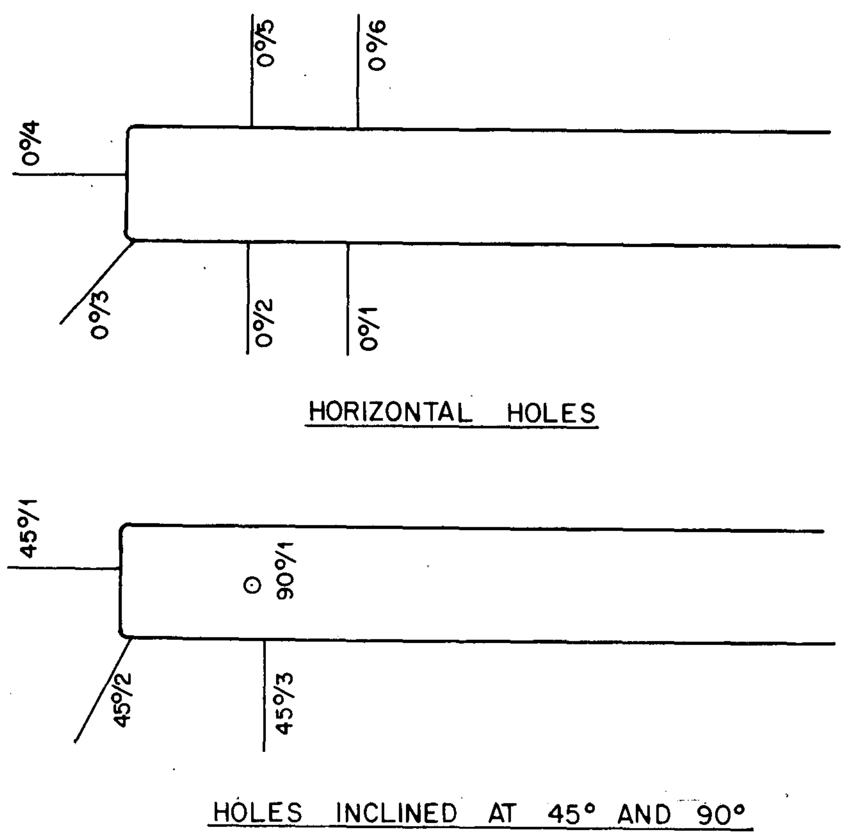

Fig. 7—Location of investigatory boreholes

mine the optimum dimensions of the pilot bore, was achieved; the best solution is no pilot bore at all.

The analyses showed that the criterion based on shear stresses does not predict rock fracture around the tunnel in a satisfactory manner. The limiting tensile strain criterion is more satisfactory in this respect in that it can predict fracture more realistically. It is believed that more light could be thrown on the applicability of various fracture criteria by *in situ* observations, particularly observations of the orientation and extent of fracturing.

Much of the difficulties experienced with the machine boring were due to sidewall fracturing and the resulting inability to grip the machine with sufficient rigidity to allow a stable drive. The fracture analyses, using a limiting tensile strain criterion, have shown that the extent of fracturing of the tunnel walls is limited to the sidewall of the tunnel, whereas no fracturing is to be expected in the roof and floor of the tunnel.

The analyses also indicated that these zones are most likely to initiate ahead of the face and enlarge behind the face owing to the presence of an opening in a highly stressed rock medium. Under these circumstances it appears that sidewall fracturing cannot be avoided and therefore the gripping problem will remain. However, the analyses also indicated that fracturing in the roof of the tunnel would be of very limited extent. Therefore, it is possible that zones of rock almost free of fractures will occur in the roof and floor of the tunnel over arcs of about 60°. The latter portions of the tunnel walls should therefore provide stable surfaces on which the grippers of the tunnel borer, if used at all times in their vertical position, can bear.

To check the theoretical predictions, it was recommended that observations should be made of the orientation and extent of fractures on the sidewalls, and that boreholes should be drilled and inspected with a borehole periscope. This would define the depths to which fracturing occurred in the sidewalls and ahead of the face.

In Situ Observations

The survey of the tunnel surfaces defined the structural geology at the site. In particular, two very well-defined bedding planes, containing soft filling material, cut across the tunnel. It is obvious that these structural discontinuities will have a considerable local influence on the fracture behaviour.

All the induced fractures observed on the surfaces of the tunnel were clearly tensile, showing clean surfaces with no evidence of crushed material due to shearing.

Sidewalls

The fracturing on the sidewalls could be clearly seen by an observer looking back along the tunnel from the face.

The fractures in the east sidewall had strike directions in the range of 10° to 20° to the tunnel axis, whereas those in the west sidewall were inclined at about 20° to 25° to the axis. The variation is believed to be due to the influence of the geological structure. Nevertheless, the agreement with the theoretically predicted orientations is remarkable. When slabs were prised out of the sidewall, it was seen that they were curved with approximately the same radius as the tunnel. This again agrees with the findings of the fracture analysis based on the criterion of limiting tensile strain. These slabs were closely packed and had thicknesses in the region of 25 to 50 mm. The dip direction of the fractures deviated from this trend in the region of the two bedding planes.

Slabs could be seen in the sharp corner formed by the face and sidewalls, and were observed to curve very sharply backwards, i.e., around the corner as predicted by the theory.

The visible fracture zones extended over an arc of about 90° on each sidewall. On the west sidewall this zone was not symmetrical about the midplane owing to the orientation of the bedding planes. This zone was found to be slightly smaller than that predicted by theory.

Face

Fractures observed at the tunnel face were associated with bedding planes and joints. Barring of the face revealed slabs 10 to 30 mm in thickness that were curved at the same radius as the cutter-head. This is as predicted by theory.

Roof

The only fracturing that could be observed in the roof was associated with the bedding planes. No fractures attributable to stress could be seen. This is again in accordance with the theory.

Observations by Borehole Periscope

The locations of ten boreholes drilled for investigation purposes are shown in Fig. 7. These holes were inspected with a borehole periscope, and the results of the observations in the horizontal holes are shown in Fig. 8. As shown, in the hole ahead of the face only one fracture was observed. The degree of fracturing increased with distance away from the face, as predicted by the theory. The depth of fracturing *in situ*, however, exceeded that predicted by theory. In the 45° and vertical holes there was no evidence of fracturing, nor of spalling in the holes. This proved the intactness of the roof and floor of the tunnel and therefore the lower stress values.

Conclusions

The theoretical investigation into hard-rock boring at depth has shown that rock fracture ahead of a bored tunnel cannot be avoided, and that a pilot bore would have undesirable effects because it is likely to aggravate tunnelling conditions. *In situ* observations confirmed the competence of the roof and floor of the tunnel, suggesting that the use of the machine grippers in their vertical position should ensure rigid support and improve the cutting conditions.

The theoretical investigation successfully explained the fracturing around a bored tunnel by the application of a simple criterion of limiting tensile strain to the results of an ideal elastic stress analysis. It is expected that similar successful predictions could be made in

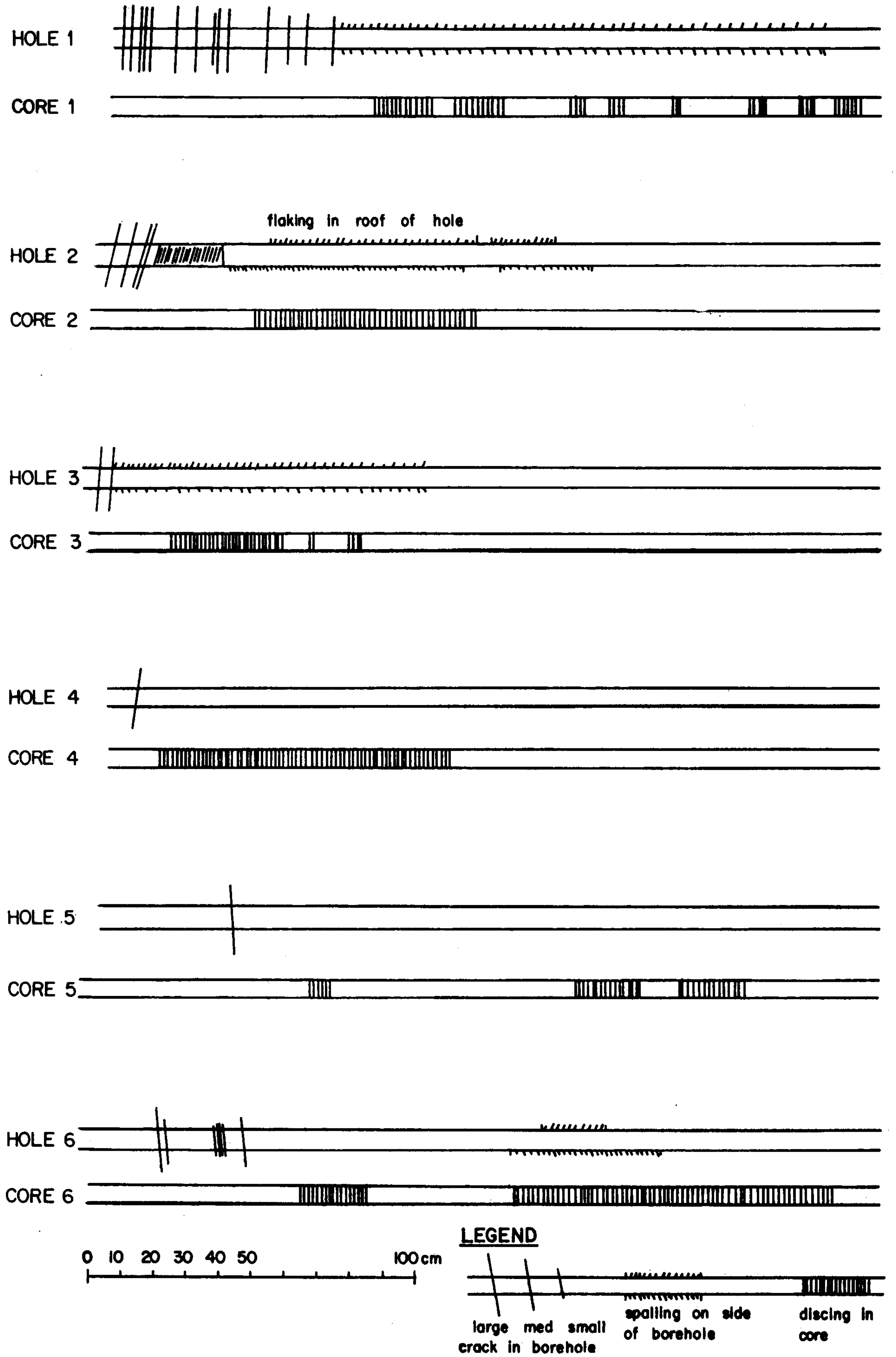

Fig. 8—Observations from horizontal exploratory boreholes

other hard-rock mining situations, for example the fracturing of the hanging wall above stope faces. The good agreement obtained may be somewhat fortuitous if allowance is made for the assumed virgin stress field and the fact that the threshold value of tensile strain was chosen rather arbitrarily. However, from the results it can be concluded that a fracture criterion based on strain could have more satisfactory application to fracture in brittle rock than a criterion based on stress. For the more general application of this concept, it would be necessary to establish a reliable threshold value for the tensile strain on the basis of rock testing.

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