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A borehole-dislocation sensor for the continuous monitoring of fracture displacement in deep mines

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SYNOPSIS

Inelastic deformation of highly stressed rock in deep mines needs to be quantified in both time and space. Since most deformation occurs by shear, continuous monitoring of discontinuities in the rock from boreholes holds promise.

The paper describes an instrument that is both cheap and reliable, and capable of monitoring such shear movements continuously. The principle of operation is based on two capacitive gravity sensors mounted orthogonally to each other in a sealed aluminium casing. All interpretations of shear movements are based on a simple relation between shear displacement and the resulting change in tilt of the sensor. A prototype has been constructed and has undergone laboratory trials with satisfactory results. Underground trials will commence shortly. The instrument as designed has the potential for other applications, both in the civil-engineering and mining industries.

SAMEVATTING

Onelastiese vervorming van hoogsgespanne rots in diepmyne moet, wat sowel tyd as ruimte betref, gekwantifiseer word. Aangesien die meeste vervorming deur afskuiwing plaasvind, hou die voortdurende monitering van diskontinuïteite in die rots uit boorgate belofte in.

Die referaat beskryf 'n instrument wat goedkoop en betroubaar is en sodanige skuifbewegings voortdurend kan moniteer. Die werkbeginsel is gebaseer op twee kapasitiewe swaartekragsensors wat ortogonaal ten opsigte van mekaar in 'n verseëlde aluminiumomhulsel gemonteer is. Alle vertolkings van skuifbewegings word gebaseer op 'n eenvoudige verhouding tussen skuifverplasing en die gevolglike verandering in die kanteling van die sensor. Daar is 'n prototipe gebou en met bevredigende resultate aan laboratoriumproewe onderwerp. Ondergrondse proewe sal binnekort in aanvang neem. Die instrument kan, soos dit ontwerp is, moontlik vir ander doeleindes in sowel die siviele-ingenieurs- as die mynboubedryf gebruik word.

Introduction

Inelastic rock deformation in deep-level hard-rock mines occurs mainly by shear, which can take place either in an incremental (or 'stick-slip' fashion) or continuously, or a combination of the two. The effects that these mechanisms may have on the stability of the rockmass still need to be determined. McGarr and Green[1] were able to measure the tilt that came in response to the enlargement of an excavation and the mining-associated seismicity at East Rand Proprietary Mines. However, the measurements were made somewhat remotely from the area where the rockmass was actually disturbed inelastically. Brummer[2] measured shear displacements in the rockmass from boreholes, using a stepmeter developed by the Chamber of Mines Research Organization. His findings indicate that there is considerable shear movement along both bedding planes and mining-induced fractures in the vicinity of stabilizing pillars at depth. The use of the manually operated stepmeter necessitated considerable skill on the part of the operator, in both gathering and interpreting the data.

In order to determine more precisely the nature of the shear movement that takes place on joints, fractures, or other discontinuities, it became evident that a continuous method of monitoring needed to be devised. Furthermore, this had to be done from boreholes since movements of the rockmass are not usually clearly manifested in the severely fractured rock that surrounds excavations in deep mines.

Since the underground environment is hostile and the continuous monitoring of shear movements is likely to take place over a period of two or more months, a simple, rugged, and reliable instrument was called for.

At a meeting held at Western Deep Levels Limited in January 1986, the suggestion of a clinometer placed on a stable platform appeared to hold some promise. A consultation of the book by Hanna[3] revealed that there was nothing suitable for the application envisaged, and work to design a suitable instrument based on clinometers began. It soon became apparent that an instrument that fulfilled all the requirements would be possible, and that it could be manufactured locally at reasonable cost.

The object of the instrument is to measure the tilt of a rigid platform that straddles a fracture moving in shear (Fig. 1). To deduce the magnitude of shear movements, the base length of the platform, the tilt angle, and the angle in the vertical plane between the borehole axis and the fracture must be known. The simple relation that was derived to link these variables to the magnitude of shear movement is given in the Addendum. Other considerations include the amount of shear dislocation that could take place before the instrument becomes trapped in the

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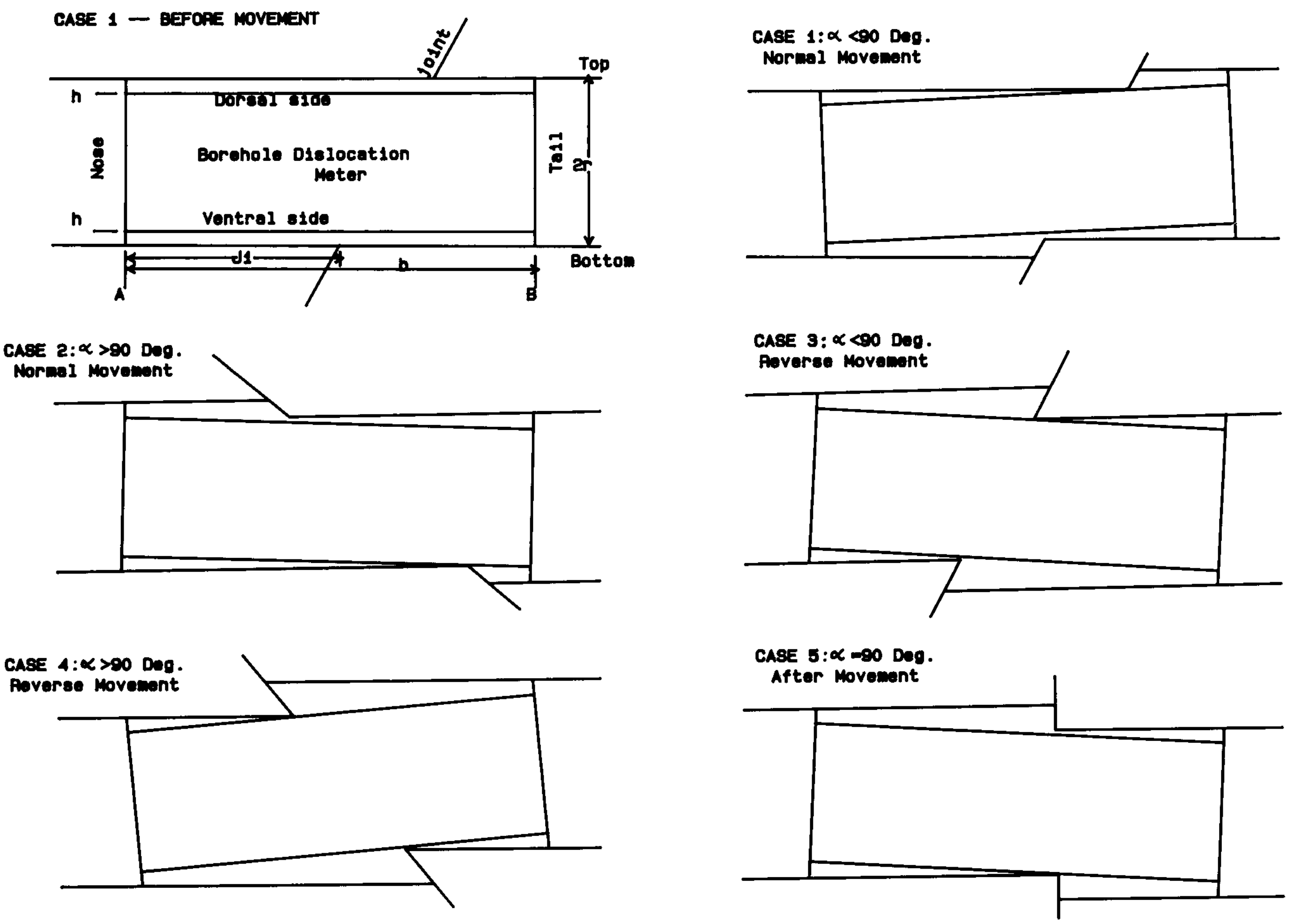

Fig. 1—Simplified line drawings of the borehole-dislocation sensor, showing its behaviour in all possible cases of borehole dislocation

sheared borehole. A series of curves quantifying this limit in all possible cases is presented in the text.

The instrument came to be known as a borehole-dislocation sensor (Figs. 2 and 3), and was designed specifically for the application shown in Fig. 4. It has the advantages of easy manufacture and operation. The interpretation of the results is simple provided that the position and orientation of active fractures are known. The cost of obtaining dislocation data is moderate, the system is rugged and reliable, and continuous monitoring is possible. The clinometers are well protected by a rugged corrosion-resistant sealed outer casing. The sealant used is an epoxy-resin glue originally specified by the aviation industry, which requires glues of this nature to retain their strength in hot, humid conditions. The major disadvantage of the system is that the sensor unit containing the clinometers is irretrievable, and that one sensor can measure movements on only one fracture. Furthermore, the position and inclination of active fractures need to be known with reasonable accuracy if the tilt information gathered is to have any meaning. It is likely that the operator will need considerable skill and patience in identifying and correctly orientating active fractures before installing the sensor unit in a borehole.

The Borehole-dislocation Sensor System

The system consists of a pitch and roll sensor, a set of stainless-steel rods for installation in a borehole, and a digital readout unit (Fig. 2). All the components are constructed of robust corrosion-resistant materials, and are sealed against moisture to ensure as far as possible long-term reliability in the underground environment.

The Pitch-and-roll Sensor Unit

The sensor unit consists of two Sperry AccuStar electronic clinometers mounted orthogonally to each other in a cylindrical aluminium casing sealed at both ends (Fig. 3). The roll clinometer is mounted in the nose of the instrument, while the pitch clinometer is mounted centrally. The casing serves no other purpose than to provide the clinometers with a stable platform and adequate protection in the underground environment. The size of the unit necessitates its use in an NXC-sized borehole.

Two fundamental problems in the design of the sensor unit had to be overcome. The first was that it must be securely locked into position in the borehole to provide consistent results, even in the event of mining-induced seismicity. Secondly, the unit must become detached from the installation rods so that they can be removed to allow the installation of other units in the same borehole.

The solution to both requirements was a 'rip cord' type of arrangement that releases spring-loaded dorsal pins that lock the unit into position. The same mechanism releases the installing rods from the sensor casing to allow their retrieval from the borehole. One disadvantage of the system is that, once installed, the unit is irretrievable.

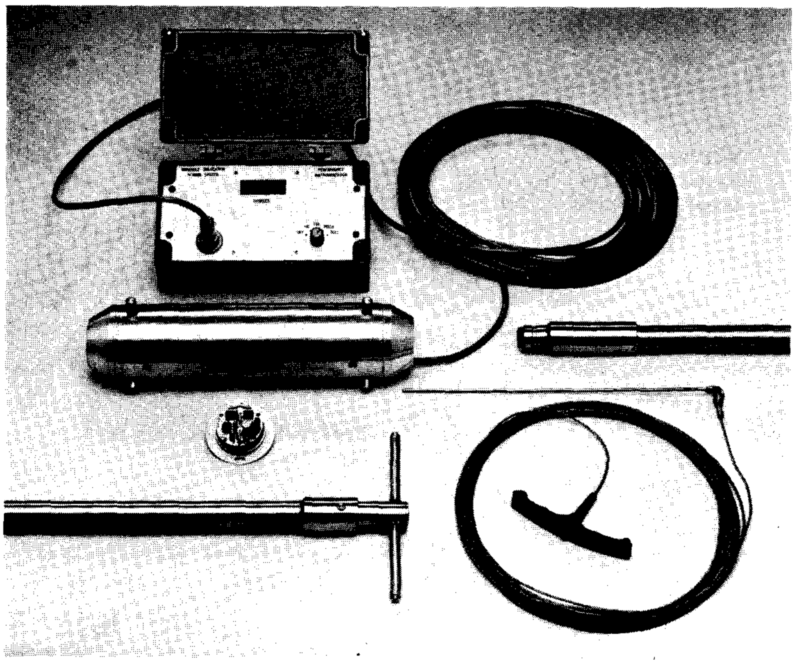

Fig. 2—The borehole-dislocation sensor system

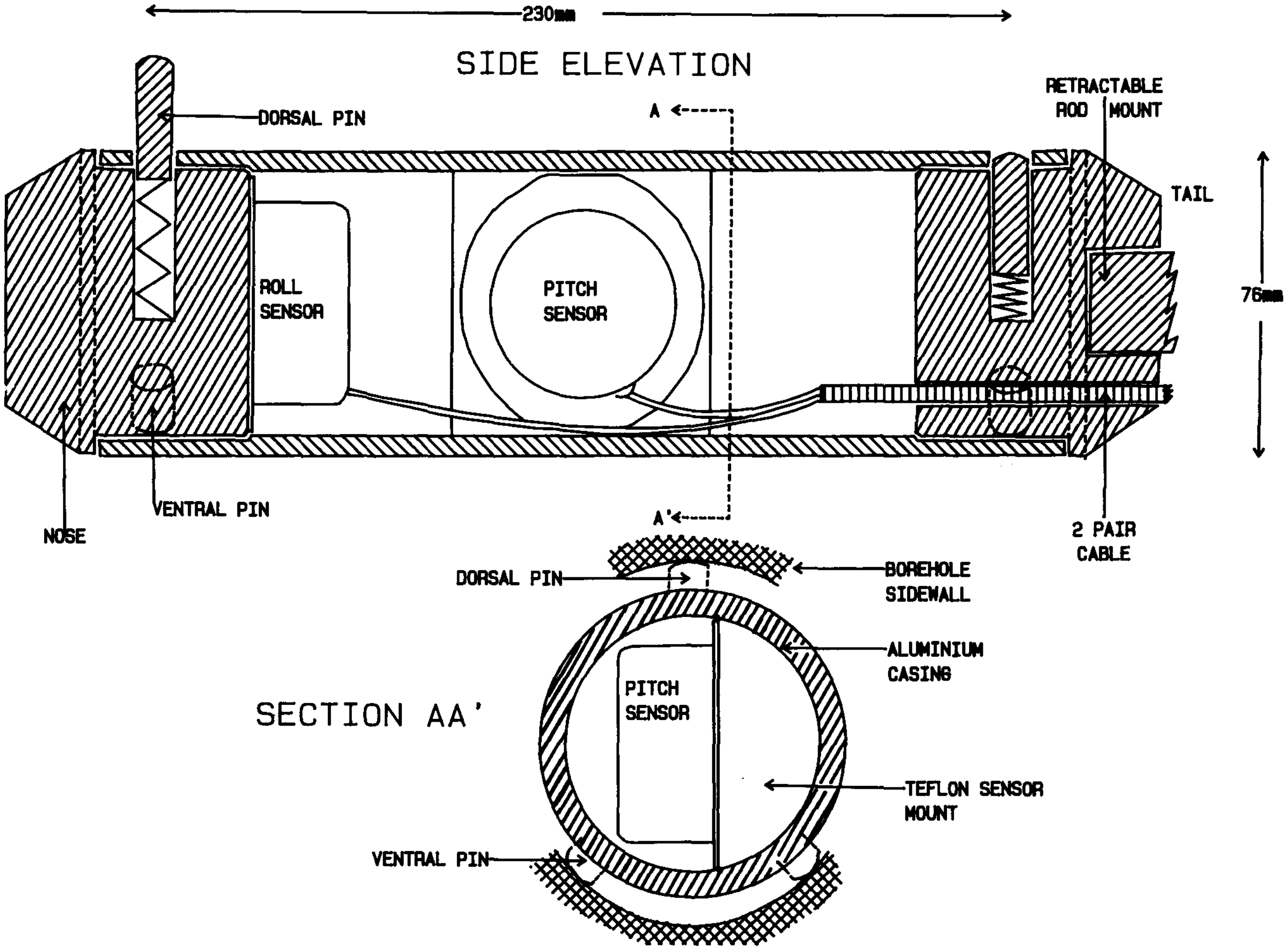

Fig. 3—Sensor unit, showing details of the components

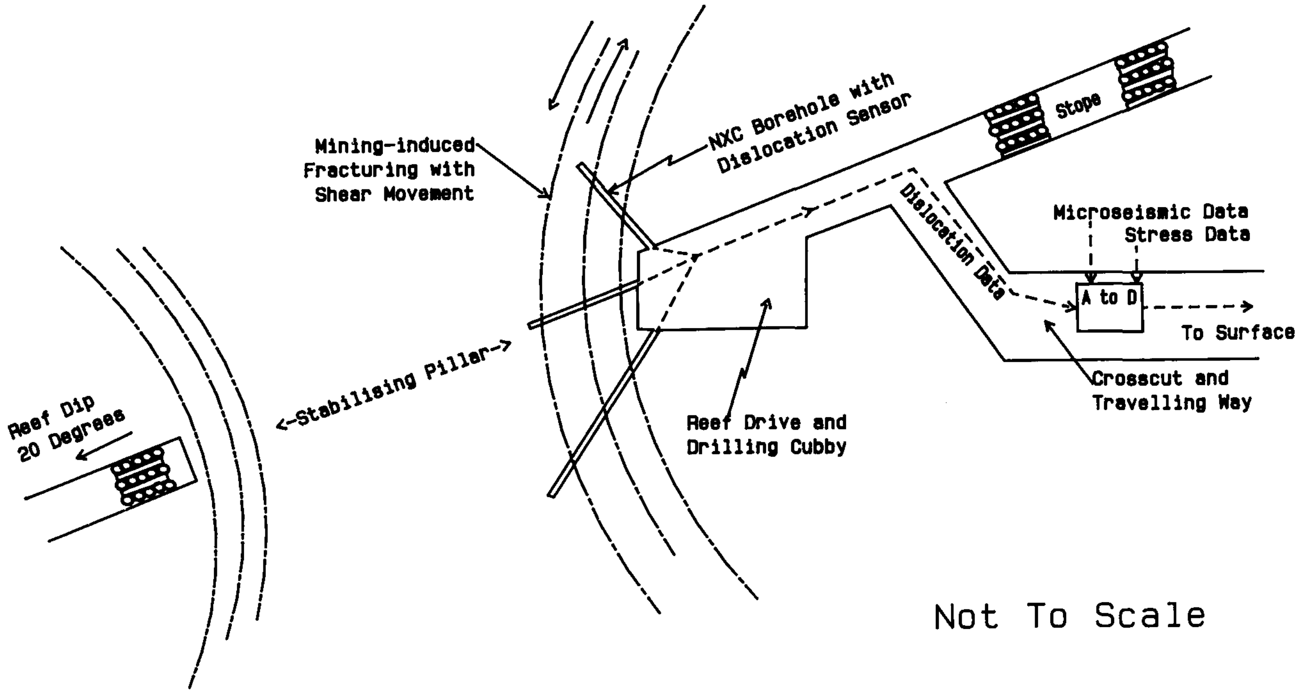

Fig. 4—Proposed layout of experiment using the borehole-dislocation sensor system at Western Deep Levels Limited

Since the locking and release mechanism is fundamental to the unit's operational success, provisional patents have been applied for.

The clinometers are capacitive gravity sensors capable of resolving angular displacements of 0,01 degree. They were chosen because of their small size, ruggedness, high reliability, and low cost. Furthermore, they exhibit long-term stability and are capable of reliable operation in temperatures ranging from −40° to +65°C. The sensor and low-power CMOS electronics make them intrinsically safe for operation in fiery mines, although certification for this purpose will be required.

The clinometers have a total range of ±60 degrees, and will measure angular displacements with an error of less than 1 per cent for cross-axis angles of up to 45 degrees. This means that the unit as shown can be installed in a borehole inclined by as much as 45 degrees from horizontal without inducing too large an error in the roll-sensor readings. The unit can be installed in boreholes inclined up to the vertical simply by modifying the sensor mounts in the casing.

The main object of the roll clinometer at this stage is to assist in orientating the sensor unit correctly during installation, and to detect any roll that may occur during the fracture-dislocation process. The user can omit either of the clinometers should the information not be required.

The Installation Rods

The rods are 1 m long units constructed of stainless steel and fitted with spring-loaded couplings for quick assembly (Fig. 2). They are designed to transmit both longitudinal and torsional forces, and to withstand the rough treatment that they are likely to encounter underground. The rod lengths are accurate, and can be used as a measure for the correct positioning of the sensor unit in a borehole.

The Digital Readout

The digital readout is mounted in a hand-held rugged alloy box, and has a range of ±60 degrees. A single multipin rugged connector connects the readout box to the sensor cable, and power is supplied both to the readout and to the sensors by a dual 12 V pack of alkaline pen cells mounted in the box. The readout resolves angles to two decimal places and has a selector switch to select the sensor required.

The Sperry AccuStar is amenable to continuous automatic monitoring and data storage, which can be achieved in most instances at a small extra cost. The necessary components are all available locally.

Cost of the System

The entire system, aside from the clinometers, is manufactured locally at moderate cost. Since all the components except the pitch-and-roll sensor can be re-used, the cost of obtaining fracture dislocation data or rock-mass pitch-and-roll data is not prohibitive. A retrievable version is possible by the use of a hydraulically operated locking-and-release mechanism, but the costs would be substantially higher than for the present system.

Interpretation of Results

The information obtained from the sensor is either a positive or a negative angle. The prime object of the instrument is to add to the original work of Brummer[2] and to clarify the mechanisms in the deformation of stabilizing pillars. Its major advantage is that a more dynamic picture of inelastic rock behaviour is obtained because the inclination of the sensor can be monitored continuously.

In order to determine the nature and magnitude of dislocation across a fracture plane, one must know the angle α between the fracture plane and the borehole axis in a vertical plane, as well as its position in the borehole. The angular information derived from the sensor can then be converted to displacement on the fracture plane by the following simple relation:

$$d = \frac{b \sin |\Delta\theta|}{\sin \alpha}, \quad (1)$$

where d = apparent displacement on the fracture plane in mm (Fig. 1)

$\Delta\theta$ = change in pitch inclination of the instrument (Fig. 1)

α = angle in degrees that the fracture makes with the borehole in a vertical plane (Fig. 1)

b = base length of instrument, in this case 230 mm.

The derivation of the above equation is explained in the Addendum.

Fig. 5 shows the resolution that the sensor unit has of fracture movement for different threshold angles of tilt versus fracture inclination. It is clear from these curves that the instrument is more sensitive to steeply dipping fractures.

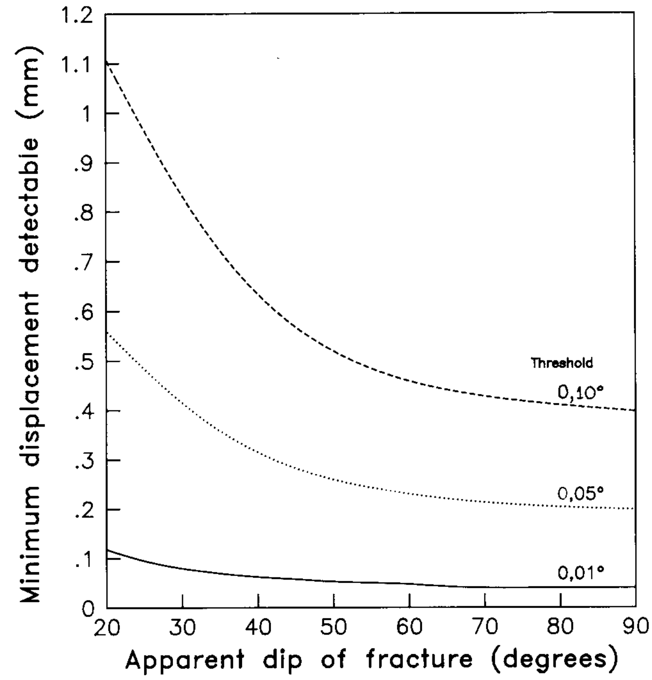

Fig. 5—Graphs of minimum displacement detectable versus apparent dip for different choices of threshold angular rotations of sensor unit

If α and the sign of $\Delta\theta$ are known, it is possible to distinguish whether the movement on the fracture is normal or reverse. The pitch sensor is wired so that a 'nose down–tail up' rotation produces a positive rotational angle, while a 'tail down–nose up' rotation produces a negative rotational angle. Fig. 1 illustrates all the possibilities of fracture movement in a borehole. The interpretation of the nature of fracture movement enables important conclusions about the driving stress field to be made. Care must therefore be taken in the measurement of α and $\Delta\theta$, especially whether α is greater or less than 90 degrees and whether $\Delta\theta$ is positive or negative.

The roll clinometer is wired so that, when the observer views the installed sensor unit from a borehole collar, an anti-clockwise rotation produces a positive angle.

After a certain amount of shear movement, the sheared borehole becomes too narrow to accommodate the sensor unit. This point, defined by the maximum angle of pitch, $\Delta\theta_{max}$, occurs when the sheared borehole sides come into contact with the sensor casing (Fig. 1). It is assumed that no debris in the borehole interferes with the process, and in this eventuality $\Delta\theta_{max}$ is a function of the borehole diameter, $2r$, the base length of the instrument, b, the clearance of the instrument from the borehole sides, h, the position of the active fracture in relation to the nose of the sensor unit, j_1, and the angle α between the fracture and the borehole axis.

For practical determination of $\Delta\theta_{max}$, a set of curves covering all the possibilities of fracture orientation and fracture movement is presented in Figs. 6 to 9. The object of knowing $\Delta\theta_{max}$ for a given situation is to determine a pitch angle beyond which pitch readings will become meaningless. In order to determine $\Delta\theta_{max}$, j_1 and α must be known. If α is less than 90 degrees and the fracture movement is normal, the curves for case 1 must be consulted. It is assumed that the fracture intersects the borehole on the ventral side of the sensor unit 120 mm from the nose pins (case 1, Fig. 1). If α is 60 degrees, say, then the first curve marked 60 degrees to be intersected by a vertical line from j_1 = 120 mm is a dorsal curve and the corresponding $\Delta\theta_{max}$ = 2,63 degrees is read off the vertical axis. This means that the top of the borehole will come into contact first at a pitch angle of 2,63 degrees. The insertion of the values of $\Delta\theta_{max}$, b, and α into equation (1) shows that maximum values of joint displacement of 16 mm can be measured with α = 90 degrees for normal movement and of 58 mm with α = 30 degrees for reverse movement. These angles are obtained when the instrument straddles the fracture in the middle, i.e. when $j_1 + j_2/2 \approx 120$ mm.

Comparison of these values with those obtained by Brummer indicates that the instrument as designed has an adequate range before pitch readings become meaningless.

There is no limitation to the amount of roll that can occur other than that imposed by the roll clinometer itself.

Initial Tests

As practical confirmation of the theoretical relations described above, a pipe with an inner diameter equal to that of an NXC borehole was constructed of galvanized iron. The pipe was cut in half 45 degrees to its axis so that the two halves could be placed end to end to simulate a fracture either orthogonal or at 45 degrees to the pipe axis. The instrument was set in the two pipes so that it straddled the 'fracture' a known distance from the nose pins (j_1). One half of the pipe was raised a pre-determined distance (Fig. 10) and the resulting angular tilt was measured. In all cases the amount of displacement, d, agreed with the theoretical quantity obtained by substitution of $\Delta\theta$ obtained from the pitch clinometer into equation (1). Practical measurements also confirmed that the curves in Figs. 6 to 9 correctly predict $\Delta\theta_{max}$ for a joint dipping 90 and 45 degrees and for various values of j_1.

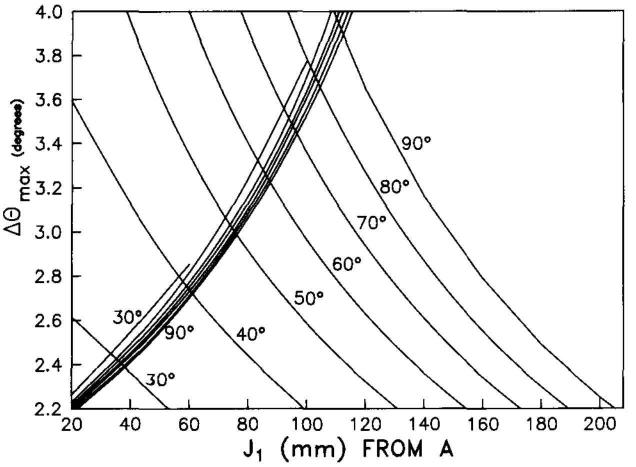

Fig. 6—Curves relating $\Delta\theta_{max}$ to j_1 for normal movement $\alpha < 90°$

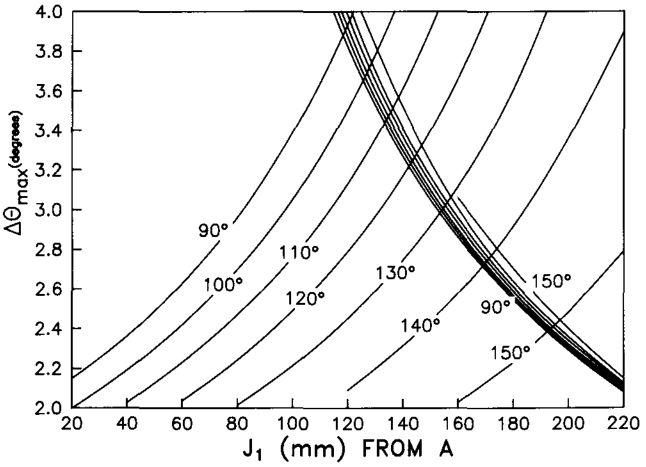

Fig. 7—Curves relating $\Delta\theta_{max}$ to j_1 for normal movement $\alpha > 90°$

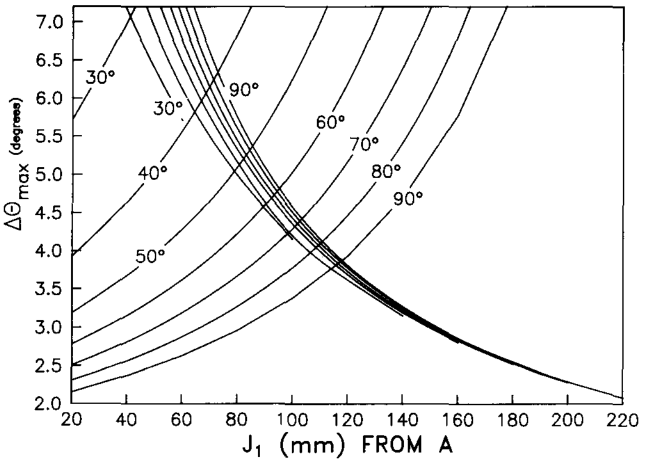

Fig. 8—Curves relating $\Delta\theta_{max}$ to j_1 for reverse movement $\alpha < 90°$

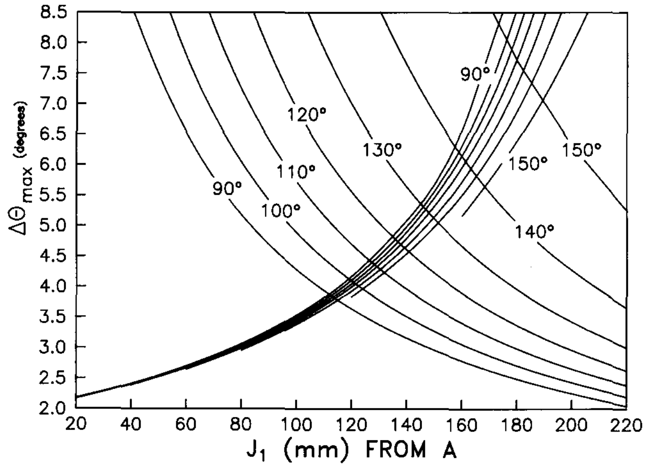

Fig. 9—Curves relating $\Delta\theta_{max}$ to j_1 for reverse movement $\alpha > 90°$

Unfortunately, the accuracy of the above tests was reduced because the pipe was distorted slightly when the spring-loaded dorsal pins were released. However, it was concluded that the theoretical predictions of d and $\Delta\theta_{max}$ agree reasonably well with reality.

Potential Uses of the System

The borehole-dislocation sensor has a number of potential uses besides the objectives outlined for its original design. In conjunction with microseismic monitoring in deep mines, it could prove extremely useful in providing seismologists with fracture-displacement data that may correspond to particular microseismic events.

Other applications include the monitoring of potentially unstable areas of rock slopes or open-pit sides from boreholes, and in the civil-engineering industry the long-term monitoring of tilt in large structures such as dam walls is possible.

Conclusions

(1) The borehole-dislocation sensor is simple, robust, inexpensive, and reliable for applications both in the mining and civil-engineering industries.

(2) It is possible to monitor rockmass tilt or dislocation continuously, and to collect and store the data automatically. In addition, its installation and operation do not require special skills.

(3) The system is amenable to permanent installation, and will be reliable in the long term if operated within the specified temperature range.

(4) The system is easy to manufacture, using materials and components that are available locally.

(5) It is disadvantaged by the facts that the sensor unit is irretrievable, it can monitor only one fracture at a time, and special skill is required to identify and orientate active fractures in the borehole.

Acknowledgements

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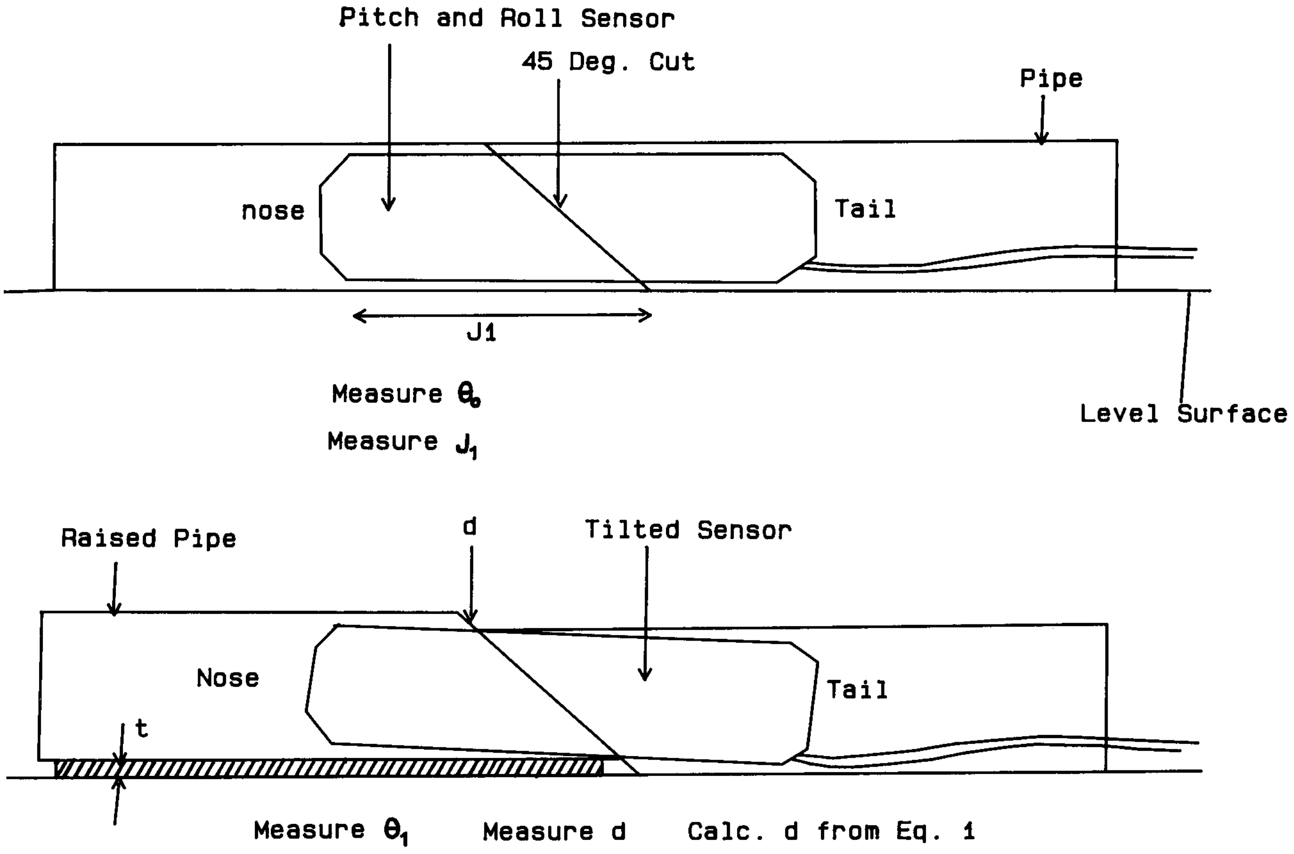

Fig. 10—The initial test

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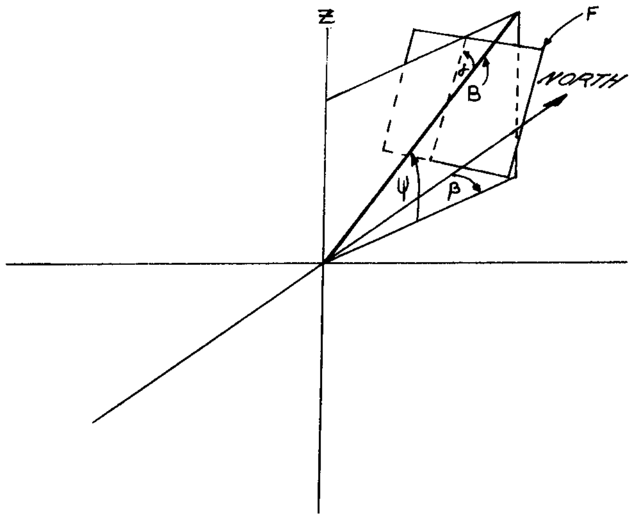
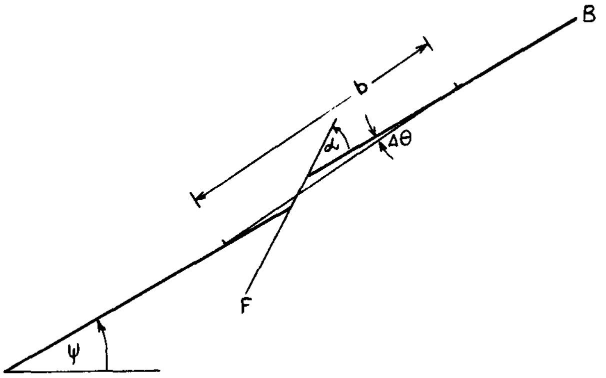
Addendum: Derivation of Relation between Fracture Displacement and Angular Information Provided by the Sensor



If an arbitrarily orientated borehole B has direction β and inclination ψ with north and horizontal plane respectively and intersects a fracture F, it will make an angle α with the fracture in a vertical plane (Fig. 10).

If movement takes place on fracture F, a rigid platform of length b that straddles it will undergo a change of inclination, $\Delta\theta$.

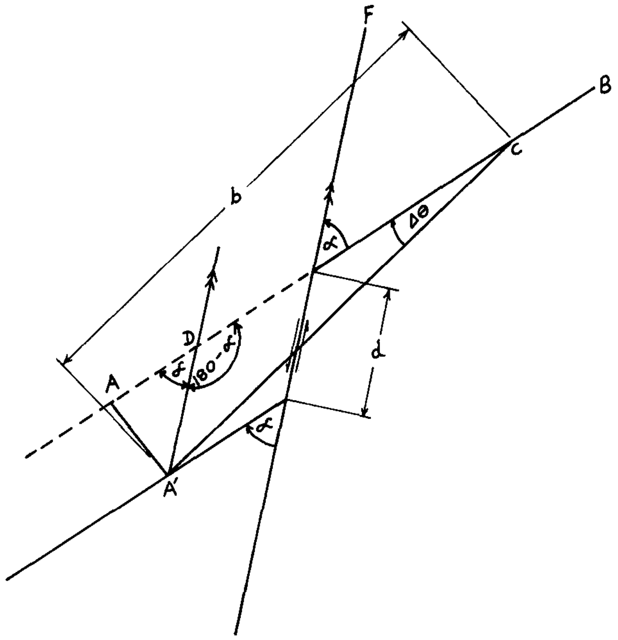


It is assumed that, before dislocation, platform of length b was positioned at CA, and during dislocation rotated through angle $\Delta\theta$ to finish at CA′. Line A′D is drawn parallel to the fault so that angle A′DA = α.

In triangle A′DC,

Angle A′DC = $180 - \alpha$.

$$\therefore \frac{A'C}{\sin(180 - \alpha)} = \frac{A'D}{\sin \Delta\theta} \text{ (sine rule)}$$



or $d = \dfrac{b \sin \Delta\theta}{\sin \alpha}$ [A′C = b, A′D = d, and $\sin(180 - \alpha) = \sin \alpha$].

To define displacement d in absolute terms, the above relation is modified slightly:

$$d = \frac{b \sin |\Delta\theta|}{\sin \alpha} \quad (0° \leqslant \alpha \leqslant 180°).$$

Tunnelling '88

Tunnelling '88, organized by The Institution of Mining and Metallurgy with the cooperation of the British Tunnelling Society, the Institution of Mining Engineers, and the Transport and Road Research Laboratory, Department of Transport, is the fifth in the IMM series of international symposia devoted to the design and construction of tunnels in the fields of civil and mining engineering worldwide.

The Symposium will be held in London from 18th to 21st April, 1988. It will cover practical developments in the safety, technology, and cost-effectiveness of all types of tunnelling, and the technical sessions will include presentations on the following topics:

- *Machines and methods*—shields, roadheaders, full-facers, drill/blast, automation and robotics, pipe-jacking, cut and cover, immersed tube, and research and development;
- *Geotechnical topics*—site investigation, ground treatment (e.g. by dewatering, grouting or freezing), lining and support, ground movements and measurements;
- *Services*—planning, surveying, contractual and legal aspects, materials supply and handling, safety and health;
- *Complete projects*—design and construction of underground excavations for mining and civil purposes; management and control of time, cost, and quality.

The inaugural address, the twenty-third Sir Julius Wernher Memorial Lecture of the Institution of Mining and Metallurgy, entitled 'When an invention is something new: From practice to theory in tunnelling', will be delivered by Dr. Ing. Gerhard Sauer, Consultant (tunnelling, NATM, rock structure), Austria, on 18th April, 1988.

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