# Development of Techniques for Evaluating Seismic Hazards of Creeping Landslides and Old Dams

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The following is the final report on Contract 14-08-0001-17761 entitled "Development of Techniques for Evaluating Seismic Hazards Associated with Existing Creeping Landslides and Old Dams." Work was done in 2 parts--downhole dilatometer and impression packer studies, and creep studies along surface lines. These are reported separately.

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# PART 1--IMPRESSION DILATOMETER STUDIES

## I. General

### A. Introduction

In a major earthquake it is possible that major loss of life and property damage will be associated with the failure of a dam and the consequent release of its reservoir. Of some 50,000 dams in the United States over 25 feet in height and with reservoirs greater than 50 acre feet in volume, about 5,000 are in seismic regions. There are probably 500 potentially dangerous old dams in California alone. It is probable that a significant proportion of these structures will have their greatest weaknesses in the foundation or abutments rather than in the body of the dam for many of the existing dams were constructed without adequate regard for geological conditions. The research described in this report responds to the need for reliable and inexpensive tools to provide essential data for seismic analysis of these old dams. The tool investigated is a downhole device to record all fractures in their correct absolute orientations, and to simultaneously determine the in-situ deformability of the rock mass.

The objectives initially proposed are recapitulated later in this chapter, together with a summary of the early efforts. Field tests with an impression packer are described in Chapter II, followed by the analysis procedure and the results from field tests. Problems involving material, operation and analysis are presented and discussed. The report also includes a literature review on dilatometers and a general discussion of the applications and limitations of the specific downhole instruments developed in this research.

The appendix contains a derivation showing the sinusoidal shape of fracture traces in boreholes when developed, standard forms for field data and data analysis, a list of vendors and a piece of Parafilm impression material.

B. Initial Objectives

The original task was to design and build a simple device to log all fractures on the borehole wall in their correct absolute orientations, and to apply a pressure to the wall in the same zone in order to measure the load-deformation relationship. The fracture log then would permit very useful interpretation of the load-deformation data so that the foundation could be subdivided into zones of defined deformability properties, ready for entry into computational models. Neither the dilatometer nor borehole jacks give data about the fractures on the walls they load, yet such data are necessary for interpretation. The operation of the instrument at successively higher pressures in the same section of the borehole would theoretically allow weighing of relative importance of fractures as well as measurement of stress and strength; but these possibilities are secondary in importance to the deformability and fracture information. The device was planned to be three feet long and capable of operating in an NX hole; it was considered important that it be fabricated cheaply so that it would be affordable in routine investigations. The new instrument, combining functions of a dilatometer and impression packer, may be called an "impression dilatometer."

C. Early Developments

There are many varieties of downhole instruments for exploring geological discontinuities (see e.g., Barr and Hocking, 1976) and deformability (see e.g., Goodman, Van and Heuze, 1970). The impression packer conceived at Imperial College, Britian, was chosen as the starting point for developing the impression dilatometer. This instrument records the impression of a borehole wall using thermoplastic film taped onto a backing of plastic foam material fixed to two aluminum shells. The expansion of a pneumatic packer expands the shells forcing the film into the surface features on the wall. Its development, construction and several trials were described by: Harper and Ross-Brown (1974?); Hinds (1974); Barr and Hocking (1976); Harper and Hinds (1977); and Brown, Harper and Hinds (1979). It is simpler and much less expensive than the Lynes impression packer used in the oil industry to evaluate effectiveness of hydraulic fracturing and hole perforations (Fraser and Pettitt, 1962; Anderson and Stahl, 1967; Hutchinson, 1974; Anderson, 1976). In the latter device, uncured rubber is wrapped directly onto a packer (Fig. 1). The impressions thus obtained are distorted and twisted, and the procedure for wrapping the rubber and obtaining impressions tends to be tedious. The Lynes impression packer is also used in the hydraulic fracturing method of stress measurement to obtain the location of induced fractures (Haimson, 1978).

The Hinds' impression packer has a pressure limit of about 200 psi;

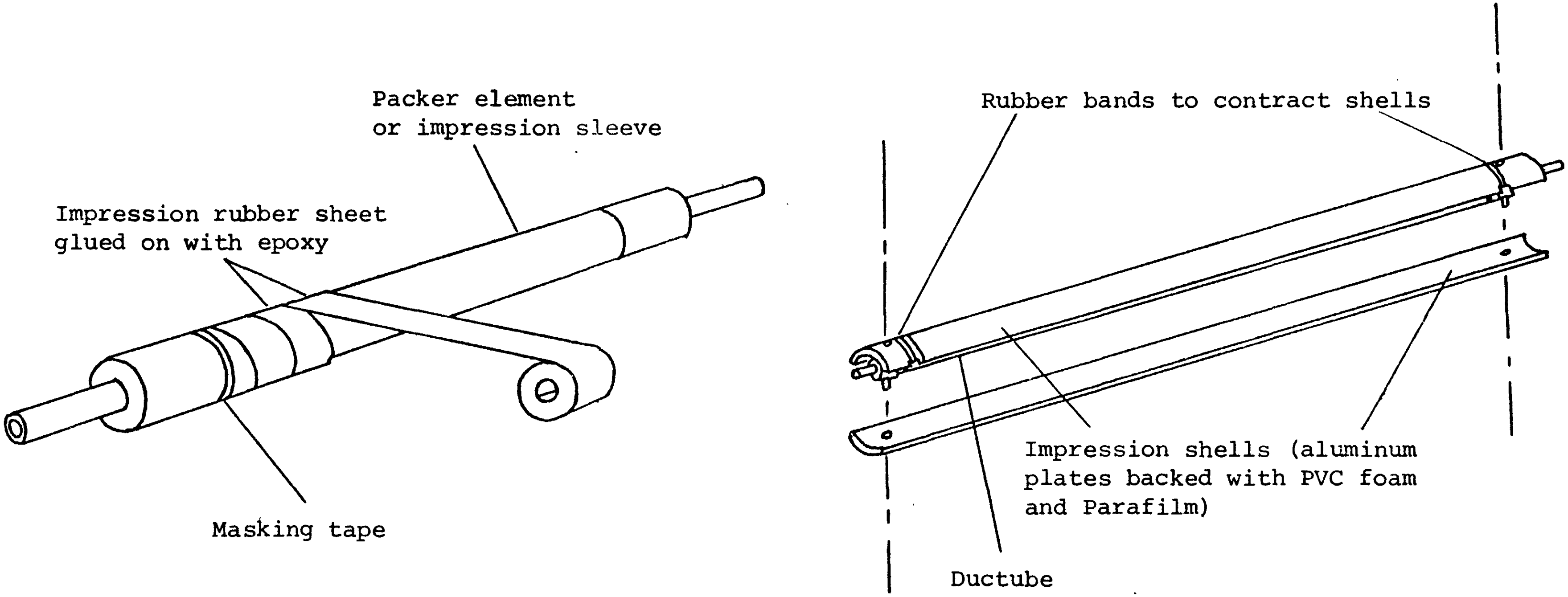


Figure 1. The Lynes impression packer (left) and the Hinds' impression packer (right).

modifications to increase this pressure limit were made in order that it could serve as a dilatometer in addition to its impression taking function. The dilatometric measurements would then be taken with the impression shell unloaded. Work on modifying the pressure seal, as well as designing a dilation measuring mechanism, was initiated by the Principal Investigator in Spring 1978, at Imperial College while he was on sabbatical there. Completion of this task was left in care of Mr. Laurie Wilson at Imperial College when the Principal Investigator returned to the United States. Mr. Wilson was able to increase the pressure limit to 360 psi with a new grip design, and finally to about 500 psi by using a larger diameter ductube in the packer; it was then Spring 1979. The project was transferred back to Berkeley at this stage, and we received an original impression packer as well as the higher pressure model in mid August 1979 (see Figs. 3 and 20).

The ductube is rated for pressures less than 150 psi by its manufacturers. A packer than can hold considerably higher pressures is needed for several reasons. First, better impressions and mapping of finer fractures may be possible by raising the pressure; secondly, it was one of the initial objectives that importance of fractures be weighed by operating at successively higher pressures; thirdly, load-deformation curves for some rocks are non-linear, and a larger pressure range is necessary for a complete evaluation of deformability. A large pressure range also improves the accuracy of load-deformation measurements since the strains produced--the base line for calculations--would be larger (Fig. 2). Finally, pressures high enough to break the rock are required to yield information on stress and strength. With

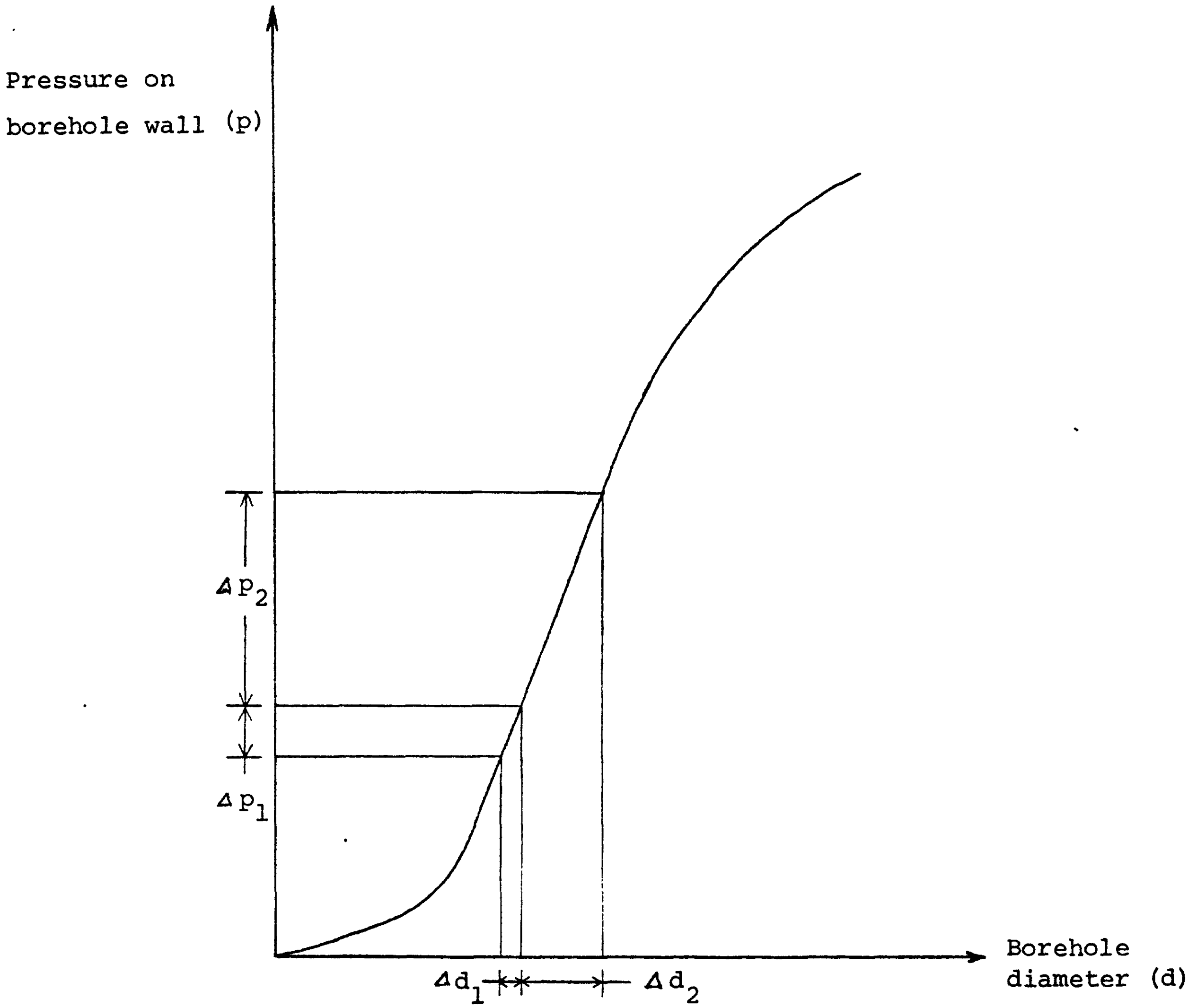


Figure 2. Response curves in dilatometer tests are non-linear for some rocks. Note also improvement in accuracy by producing a higher pressure. ($\Delta p_2$ and $\Delta d_2$ could be measured more accurately than $\Delta p_1$ and $\Delta d_1$).

these requirements in mind, a production-injection packer (SCI-PIP) reinforced for high pressure was ordered from the Lynes Company in late May 1979; it was designed to hold 4,500 psi differential pressure.

In the meantime, we assembled the impression packer and gathered the parts necessary for its operation. The thermoplastic film (Parafilm) recommended by Hinds was obtained and cut into appropriate sizes; various methods for mounting the Parafilm were tried; taping with silver cloth adhesive tape (duct tape) was chosen over the others (including partial melting of the Parafilm with a torch). The parafilm can be dismounted by cutting around the tape with a knife blade. Stiff water pipes were gathered for placing the instrument into boreholes; these were connected to the packer and tightened until painted reference marks aligned to give an absolute orientation for the instrument downhole (Fig. 10). Pressure regulators, pressure gauges, polyurethane (Polyflo) tubings, a steel water reservoir and a bottle of compressed nitrogen were also acquired in preparation for field testing.

## II. The Impression Packer

### A. Field Tests: Sites and Equipment

In late October 1979, an opportunity for trying the impression packer in some boreholes opened up as the Mt. Carmel Tunnel in Zion National Park was closed at night for drilling operation. The tunnel was built at times only several feet behind a sandstone cliff several hundred feet high; it was disrupted and exposed by a rockfall in 1958, and its stability has been a concern to the Park Service ever since.

Arrangements were immediately made to ready the impression packer for field testing. A trial test was performed in the borehole inside a large granite core to check out any unforeseen problem before departure for the field.

This granite core (the Ultra Large Stripa Core) is about 94 cm in diameter and 166 cm long, with an NX hole drilled along its axis. Since the core is so conveniently located at Richmond Field Station and has been subjected to extensive fracture and hydrology investigations (Thorpe, et al., 1979; Thorpe, et al., 1980), more tests have been and will continue to be conducted in its center hole. Fig. 3 shows the impression packer and the granite core.

The original impression packer was employed in these field tests, as the high pressure model was not yet ready. Water under gas pressure was used for inflation during the first tests at Richmond Field Station and at Zion, since we were anticipating future deformation measurement by monitoring the volume of water that enters the packer; but compressed air was utilized instead in later tests to simplify the equipment and procedure. A schematic diagram of the system is shown in Fig. 4. The procedure adopted in these tests was listed in the Attachment to the Twelve Month Technical Report (Chan and Goodman, 1980) for this project; the modified procedure after incorporating some improvements is given in section D of this chapter.

Whereas no significant operational problems were encountered during the tests conducted at Richmond Field Station, testing operations were less smooth at Zion. In the first night, only 3 tests were completed because 3 hours were spent in replacing a burst ductube. The

Figure 3. The impression packer and the Stripa core. Four rubber bands were used to tie Parafilm down on the right impression shell.

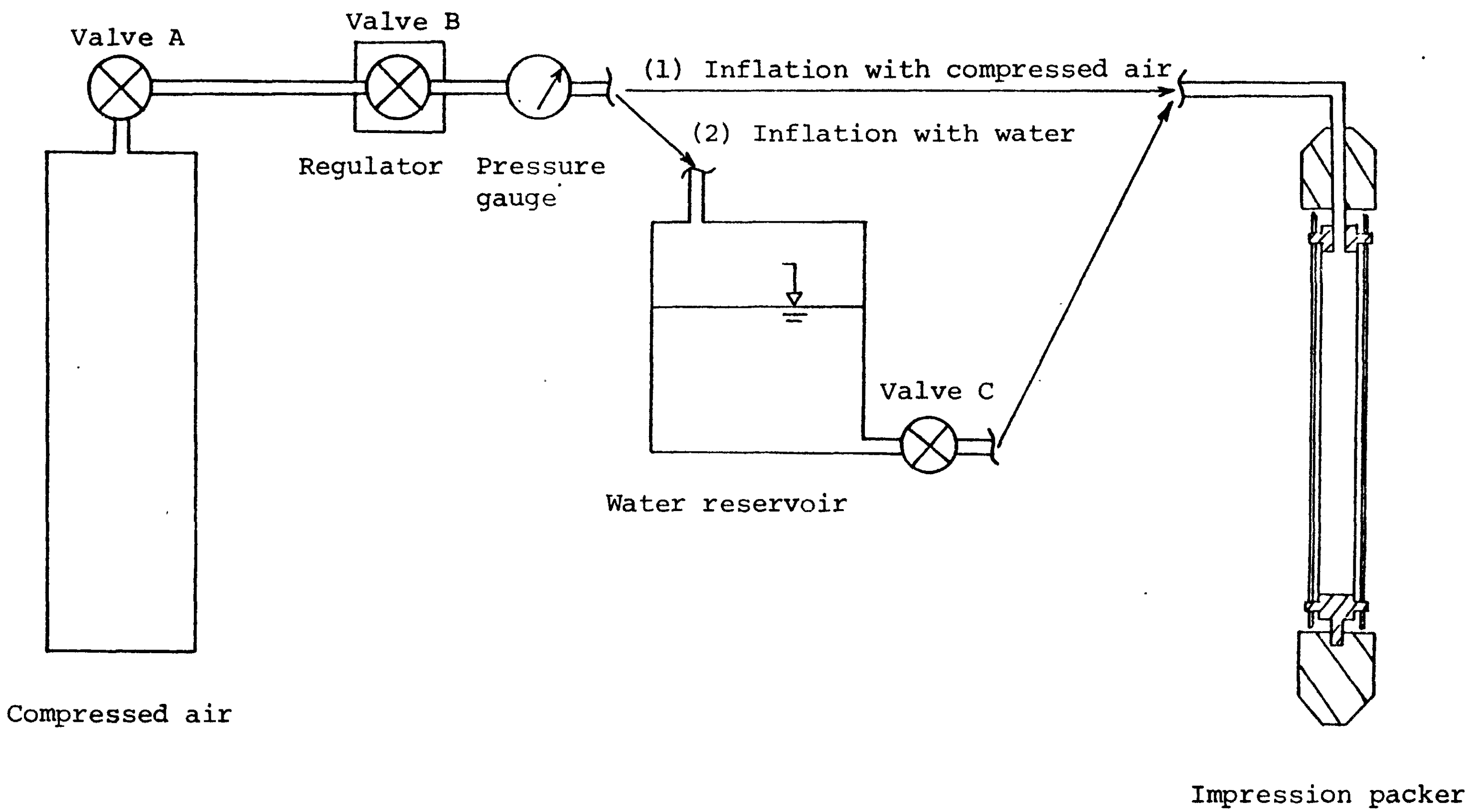


Figure 4. Schematic diagram of the impression packer system.

packer overinflated in a collapsed concrete section of the first hole tested, an unlogged hole 5.7 feet long (Fig. 5). Eight more tests were made in a logged 44.7 feet long hole on the second night; both holes tested were sub-horizontal.

B. Analysis of Impression Records and Results

To interpret the impression records, the apparent aperture $e_a$, and the quantities $L_I$, $L_{II}$, $S_I$ and $S_{II}$ (Fig. 11) were measured with a scale for each fracture trace. The fracture traces are fairly easy to distinguish from artificial wrinkles by their natural roughness; they are also very durable, fading little in the months that have elapsed.

Two angles, $\alpha$ and $\beta$, were first calculated for each fracture trace. $\alpha$ is 90° minus the maximum "apparent dip" angle of the fracture (or the maximum "apparent dip" angle of the normal to the fracture) with respect to the borehole axis, and $\beta$ is the maximum "apparent dip" direction measured clockwise from a reference line when viewed in the direction of drilling (Fig. 6). Knowing the direction and inclination of the borehole axis as well as the location of the reference line, the absolute strike and dip of the fractures can be obtained with stereographic projection techniques (Section D, Fig. 14). It was noticed that only about the middle four feet of the Parafilm is pressed hard enough against the borehole wall; we designated that section as the "nominal coverage." The location of a fracture is given by D, the distance along the axis between the ground surface and the point where the axes intersect the fracture (Fig. 7). Appendix 3 (Table 4) shows a standard data analysis form corresponding to the analytical procedure introduced in Sections C and D of this chapter.

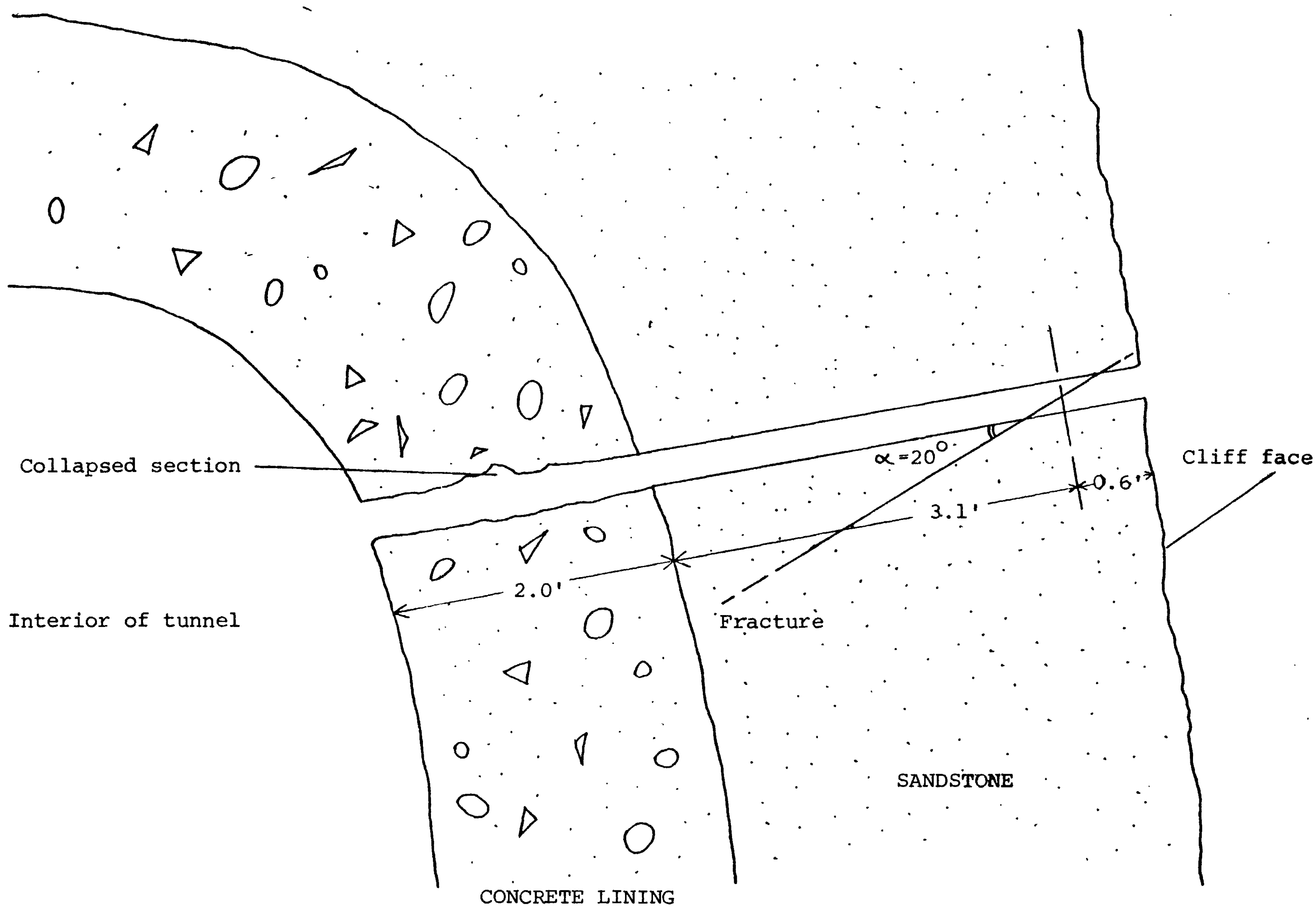


Figure 5. Schematic cross-section showing the 5.7 feet long unlogged hole in Mt. Carmel Tunnel. The packer overinflated in the collapsed concrete section, and only one fracture was mapped in this hole.

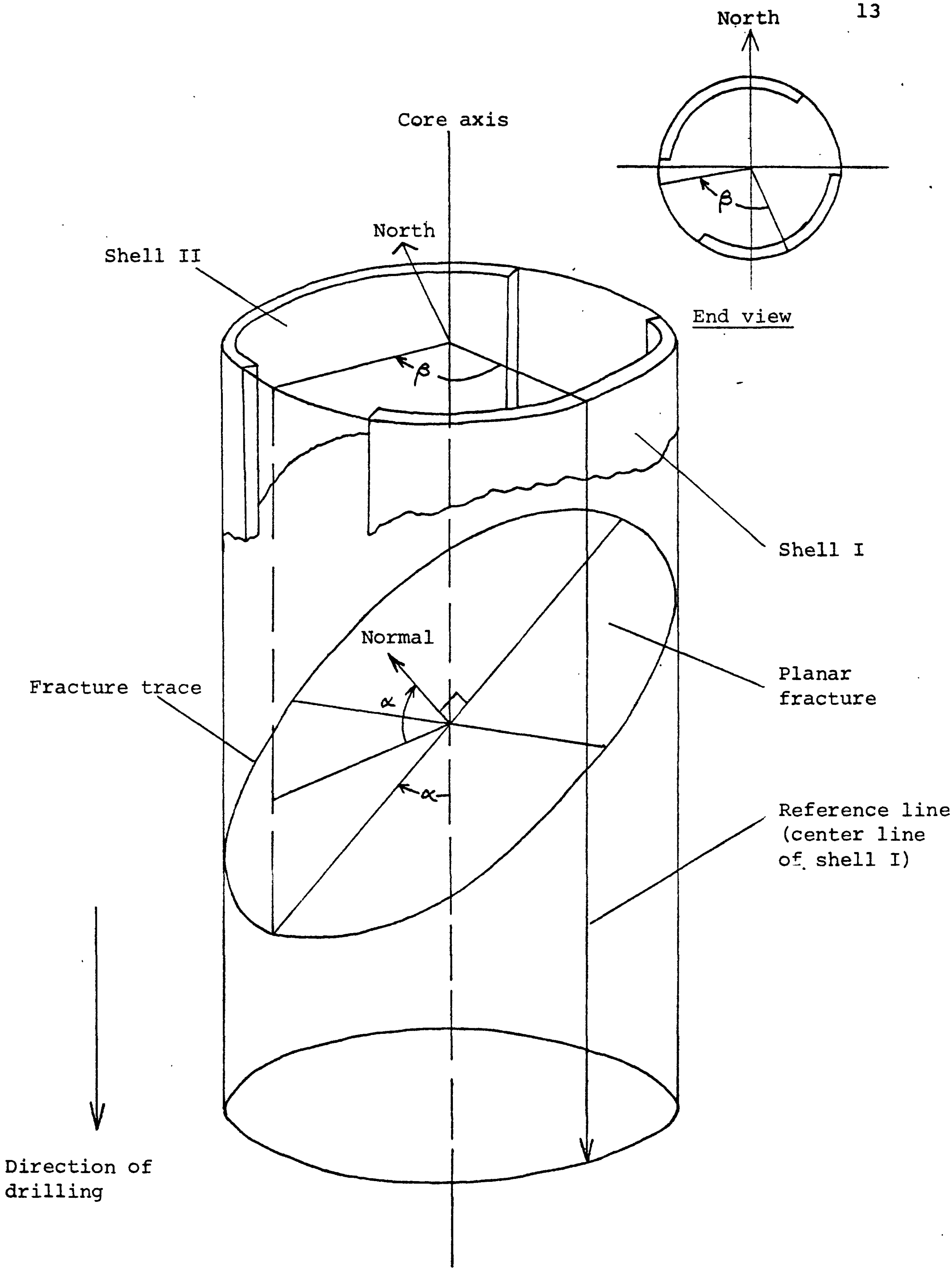


Figure 6. Two angles ( $\alpha$ and $\beta$ ) are used to fix a planar fracture with respect to the core axis and a reference line.

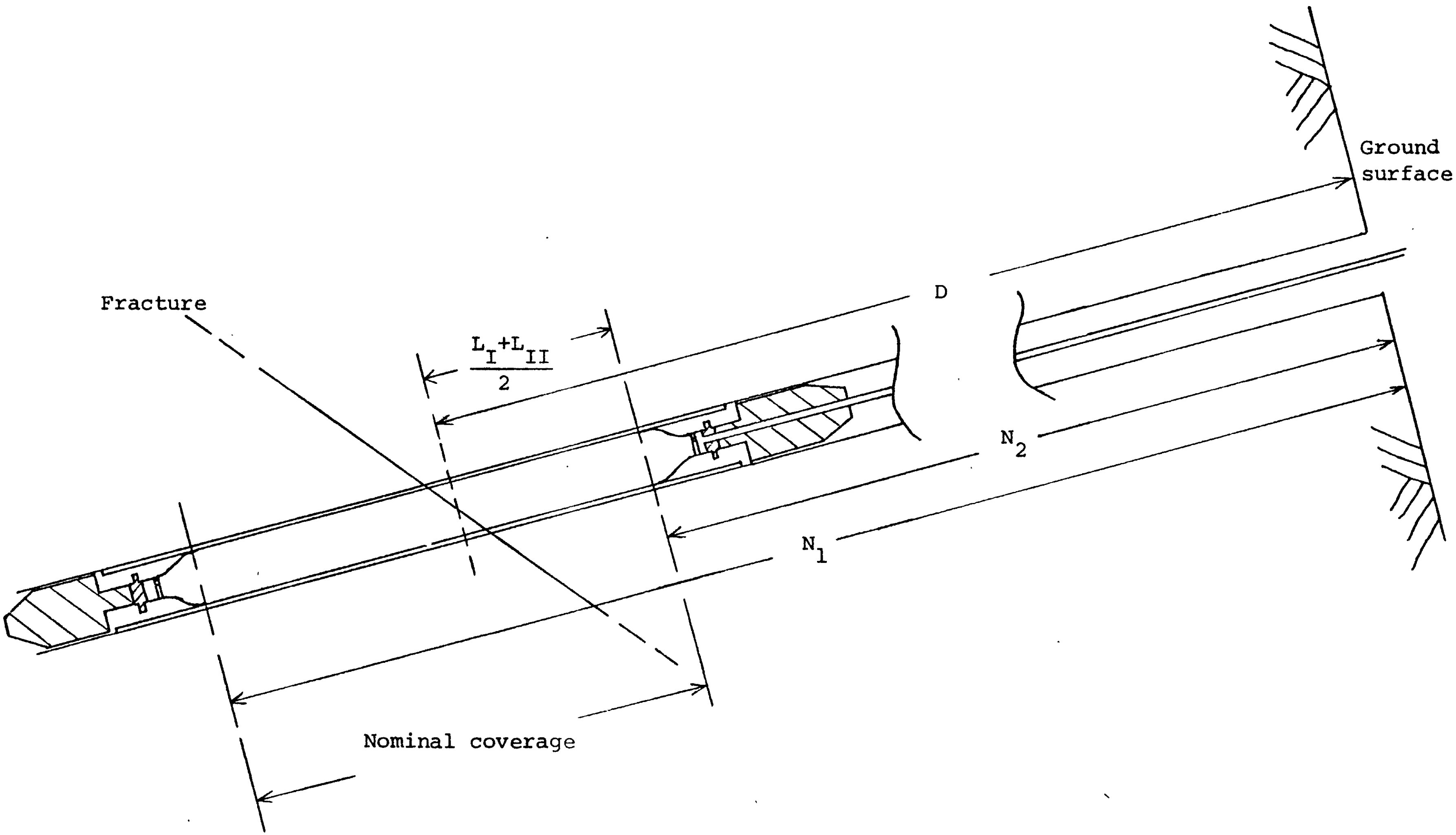


Figure 7. Nominal coverage of an impression packer test and location of a fracture.

Only two major fractures out of six were recorded by the first impression test in the granite core. However, only the upper four fractures were contained within the "nominal coverage." During tests performed later, the anchor rock bolt and the bottom borehole guide were removed to allow the packer to go deeper into the hole; as a result, one additional fracture (fracture C) appeared on the impression in a test at the maximum house pressure of 75 psi. The results of tests performed in the granite core are depicted in Fig. 8.

One fracture was mapped inside the short unlogged hole at Zion (Fig. 5). The direction and inclination of the hole were unknown, making it impossible to calculate the absolute attitude of the fracture; also, no core log was available to check the accuracy and completeness of the result.

Impression records from the long logged hole at Zion are more encouraging. All except one very tight and closed joint on the core log were picked up by the impression packer, while several fractures that had been logged as "Mechanical Breakages" were seen in the impression, proving that the core log was wrong (Fig. 9).

C. Problems and Possible Solutions

Several problems related to impression material limitations, operational difficulties and analytical difficulties are discussed below. Some arose during field tests or in analysis of the results, while others have not actually occurred but were anticipated. Solutions already implemented or suggested are given wherever possible.

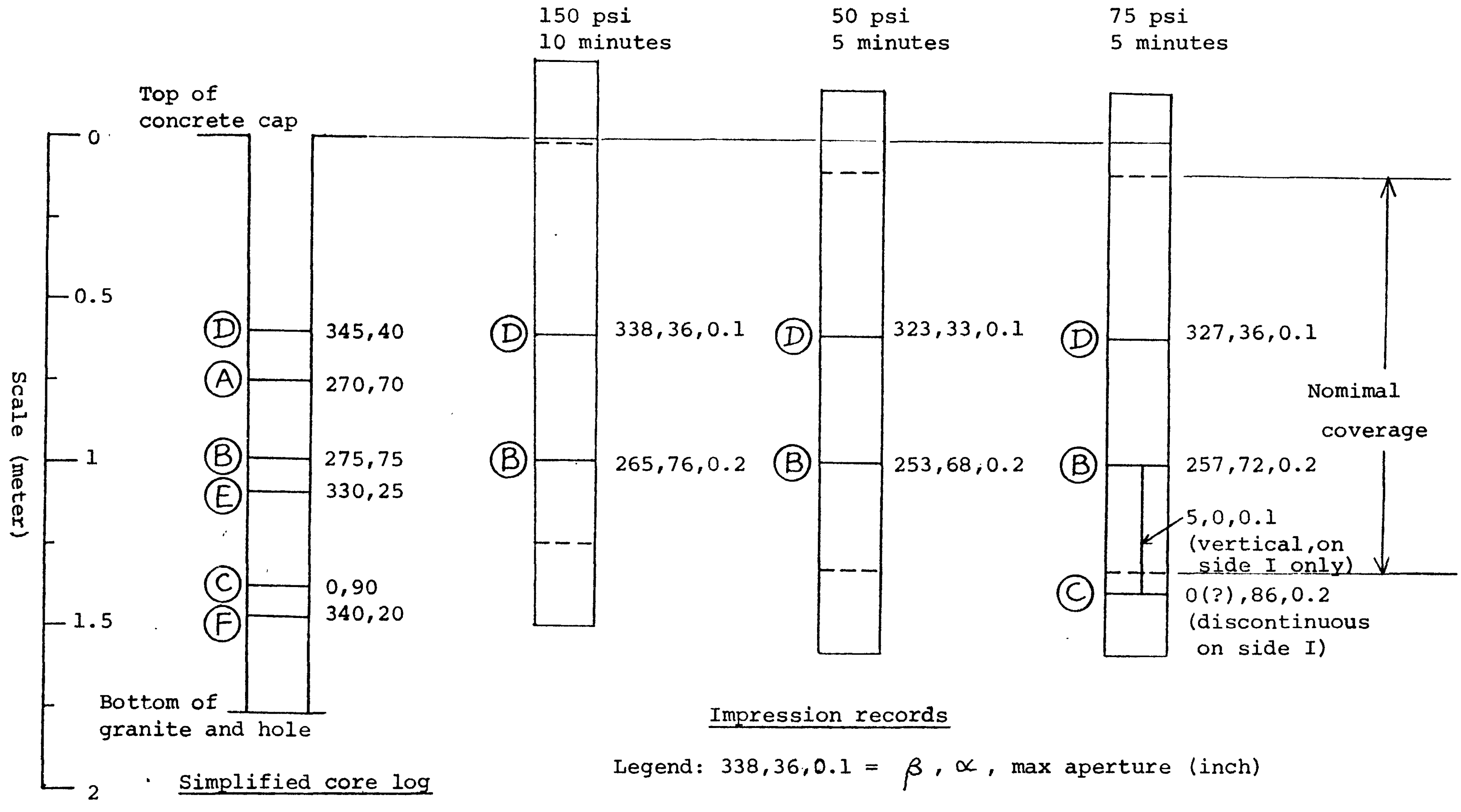


Figure 8. Results of tests in the Stripa core. Fractures D, B, and C have been judged to be the three main water conduits in the core by permeability tests.

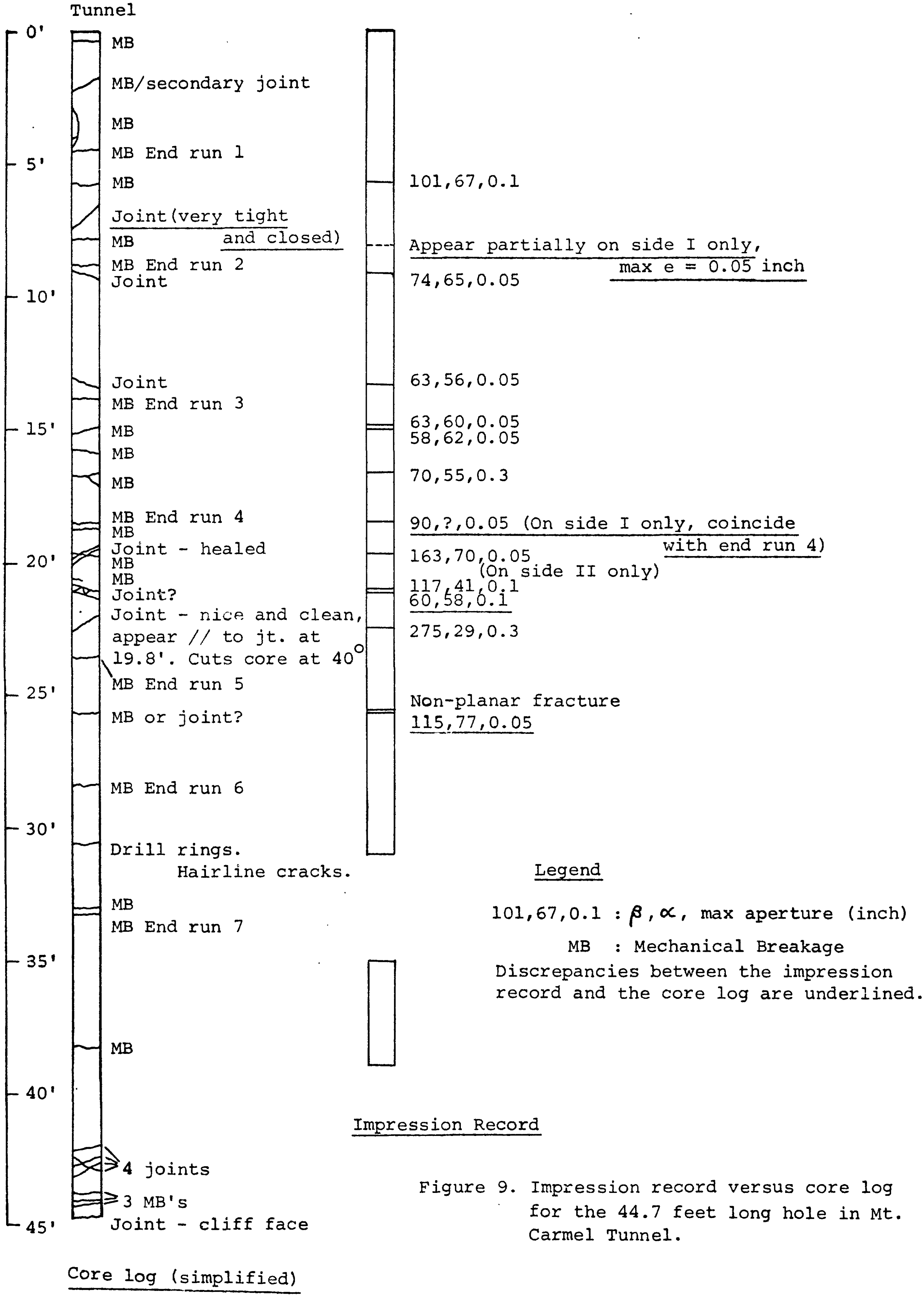


Figure 9. Impression record versus core log for the 44.7 feet long hole in Mt. Carmel Tunnel.

1. Impression material limitations

a. Sensitivity with respect to aperture

As noted before, some fractures were found to be missing from the first impression taken inside the granite core. To investigate why, we performed additional tests with the "nominal coverage" moved downwards to include all the six major fractures. The two open fractures prominent in the first impression showed strongly again after holding the pressure at 50 psi for 5 minutes. One additional fracture (fracture C) appeared on the impression when the pressure was increased to 75 psi; this was the maximum available house pressure. The minimum aperture recorded is about 1 mm, apparently in agreement with previous experience.* At this time, further tests at higher pressures and longer durations are planned to determine the minimum aperture that could be "read" using Parafilm as an impression medium. However, it is encouraging to note that the three fractures recorded have been judged to be the three main water conduits in the core. These observations were made by using packers to isolate flow entrance to each of the six major fractures (Thorpe, 1980).

b. Imaging for display and permanent storage

Some of the traces are hard to recognize. Putting the Parafilm on overhead projectors to magnify the image helps in measuring apertures. Some further image enhancement is desirable. Although the

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*Professor M. S. King informed us that a minimum aperture of about 1 mm was also found to be requisite for a good impression in tests performed at Imperial College.

Parafilm records are fairly durable, it is necessary to transfer the data to reports. Photocopying did not produce adequate results, and using the Parafilm as negatives for developing prints is too expensive. An imaging system with paint followed by xerography may prove suitable.

c. Temperature limits

The effects of temperature on the Parafilm were unknown, and we were worried about its applicability in extreme winter or summer. By heating a piece of Parafilm with an artificial mark in water, we found that it began to soften at about 60° C, stuck to itself and distorted the mark at about 70° C; it melted at about 95° C. A brochure later obtained from its manufacturer (American Can Company) also indicates that the film becomes soft and sticky at about 130° F to 150° F (68° C). No observable change occurred when a similar piece was left overnight in a refrigerator. The recommended storage temperature for the Parafilm is 45° F to 90° F (7° C to 32° C). Hence the Parafilm should be adequate for use in most climates, and only in geothermal areas or extra deep applications would problems arise. Water has no effect on the impressions.

d. Other impression materials

Parafilm was considered to be the best material of four tried by Hinds (1974). Aluminum foil, not included in the comparison, was suggested as an alternative later. A trial test using aluminum foil was run inside the Stripa core; the same fractures were mapped with somewhat more relief, but there are problems with buckling, tearing, and especially artificial wrinkles. Storage is also a problem since the foil develops creases when rolled, and the traces are easily damaged on contact.

2. Operational difficulties

a. Holding Parafilm in place

Various methods for mounting the Parafilm onto the shells were considered, including use of heaters, and clips on the ends. The solution we now consider to be most efficient is to tie the Parafilm down with rubber bands (Figs. 3 and 20). Clips may still be incorporated with the rubber bands to ease handling.

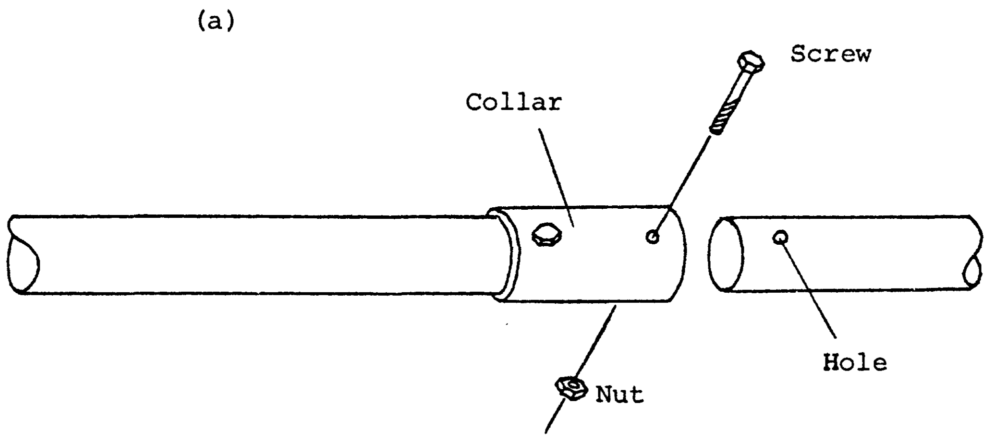
b. Assembling and aligning rods

It was very tiring and time consuming to assemble the water pipes in the manner described in Section C of Chapter I. There are a variety of methods to orient downhole instruments (e.g., see Barr and Hocking, 1976); but to enable operation in sub-horizontal holes, a stiff insertion column will be necessary for pushing the packer into place. Quick-coupling and self-aligning rods are needed. An example of such rods is shown in Fig. 10.

However, even the use of these rods to orient the packer will still take up considerable time when the depth increases. Other methods of orientation such as use of borehole compass or mercury level lights which allow lowering with cables would be more appropriate for such cases. This is possible only for tests in sub-vertical holes.

c. Need for field data sheets

Instead of testing the section from 39 to 43 feet depth in the long hole at Zion, the section 35 to 39 feet was tested due to a miscalculation of the length of rods required. A more systematic approach was needed. In response, a standard form for data taking was designed (Appendix 2, Table 3).



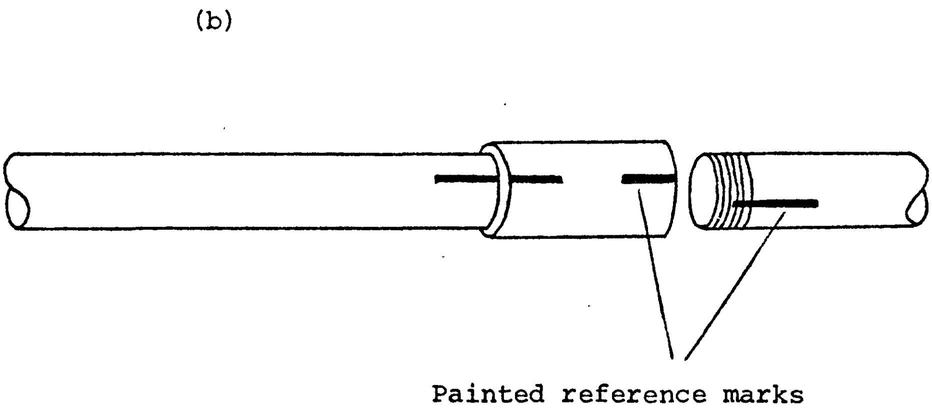




Figure 10. (a) Quick-coupling and self-aligning collars versus (b) painted reference marks for giving absolute orientation down hole.

d. Hole caving and rupture of the packer

Bursting of the packer and deforming of the impression shells is a potential problem even though the time lost in replacing a burst ductube could be shortened with practice. This happened in our tests at Zion and in a case reported by Brown, et al. (1979). Kujundzic (1964) suggested doing a caliper study of the hole if such danger exists. The procedure adopted by Brown was to case the hole and place the packer 1/2 m ahead of the casing. He also suggested the use of strengthened side plates in such cases. Pentz (1980) suggested filling the hole with drilling mud, in which case the effect of mud cake on the fractures will have to be considered. The use of steel reinforced packer from Petrometalic should alleviate this problem.

e. Inflation, deflation, and retrieval of the instrument

If the packer is inflated with water, deflation would be a problem in the case where the hydrostatic head alone is enough to expand the packer; forced retrieval would damage the impression record. Since the packer is inflated by about 50 psi, the problem arises below about 100 feet of water. A relief mechanism is therefore required. No deflating problem should exist if air is used to expand the packer; also, the equipment and procedure would be simplified by using gas instead of water.

The danger of losing the packer downhole is ever present. A fishing tool head was designed for the top of the instrument for its retrieval in an emergency.

3. Analytical difficulties

a. Reference marks, base grid and standard traces

During analysis of the data, we noticed that some sort of reference marks on the shells which transfer onto the impression record would facilitate the measurement of $L_I$, $L_{II}$, $S_I$ and $S_{II}$ (Fig. 11) for determining the orientations of fractures. However, solid markers put between the Parafilm and the underlying P.V.C. foam do not work because the P.V.C. foam is more compressible than Parafilm. Now, reference marks are painted on the shells and marked correspondingly on the Parafilm by ball pen before each test.

A base grid that corresponds to the reference marks on the shells and the Parafilm, calibrated to read $\beta$ directly, has been constructed. Sine curves simulating intersection traces of plane surfaces with boreholes have also been generated to facilitate determination of $\alpha$, especially for traces that appear only partially (Fig. 13). Both the $\alpha$ and $\beta$ determinations require knowledge about size of the hole; NX holes were assumed in the construction of the base grid and standard traces, analysis of results in different size holes could be done by measuring the L's and S's or by constructing an appropriate base grid and traces.

b. Field interpretation

For visual interpretation of the data on the site, the impression record may be placed onto a tube with outer diameter corresponding to the diameter of the hole when the tube is oriented parallel to the hole axis, strikes and dips may then be measured with a compass (Barr and Hocking, 1976).

c. Effect of drilling

The effects of drilling on the apparent aperture and apparent

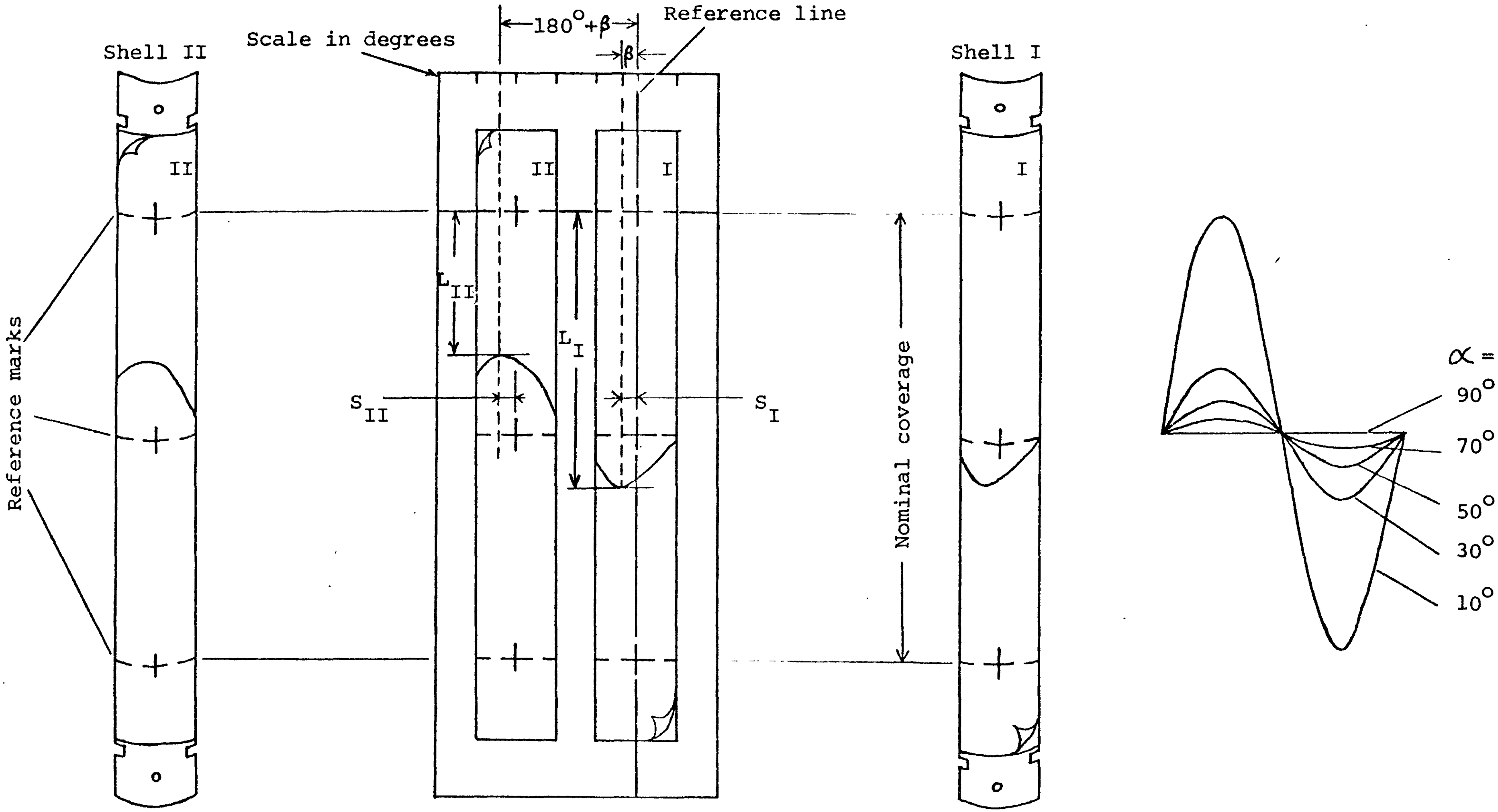



Figure 11. Reference marks, base grid, and standard traces.

attitudes of fractures are unknown (Fig. 12). Since flow rates are proportional to the cube of the apertures, this may significantly affect interpretation of the results.

d. Non-planar or discontinuous fractures

The fracture traces are not always sinusoidal in shape as they should be if the fractures are planar (Appendix 1). Furthermore, apertures of fractures sometimes vary on a given trace and may even be discontinuous (Fig. 13). The impression packer thus documents the perfection of fracture planarity. The results should be interpreted with this in mind.

D. Modified Procedures for Operation and Analysis

After the considerations suggested in Section C are implemented, the procedures for operation and analysis are modified to those given below.

1. Operational Procedure (refer to Appendix 2, Table 3, Field Data Form and Fig. 4).

For each new borehole tested:

a. Record boring number, location and size of borehole;

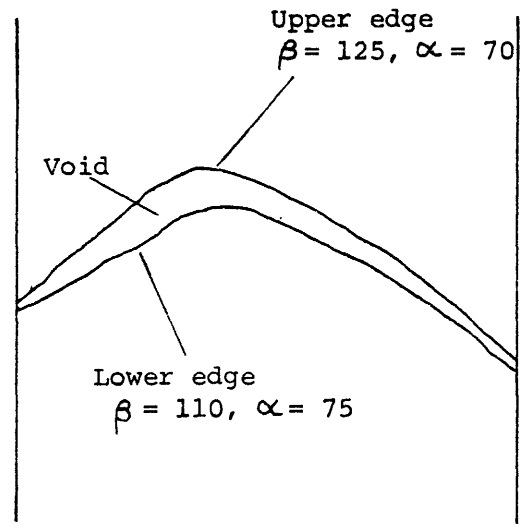
b. Measure and record its direction and inclination.

For each test in a borehole:

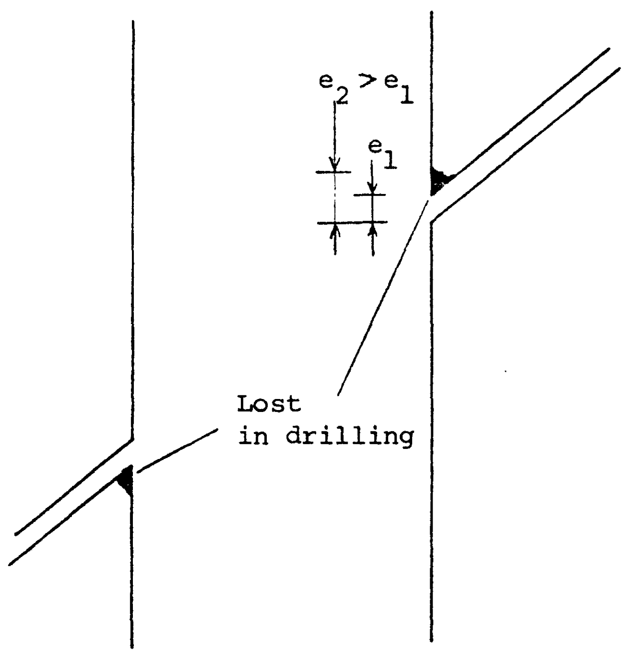
a. Record boring number;

b. Determine section of hole to be studied (nominal coverage), calculate and mark off appropriate length of rods or tubing;

c. Cut and tie Parafilm on shells of packer with rubber bands;




(a) A fracture trace on an impression record




(b) Schematic longitudinal cross-section of a borehole and a fracture.

Figure 12. Effect of drilling on apparent attitude and aperture.

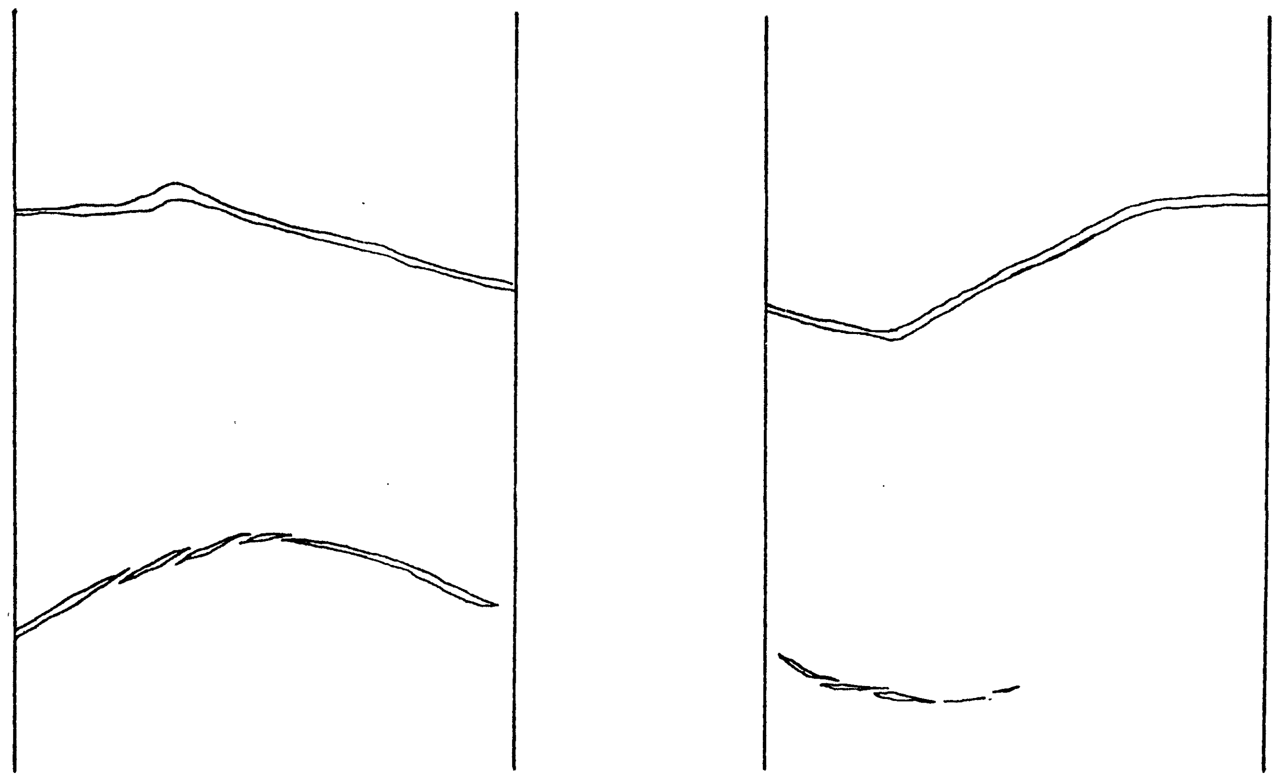


Figure 13. Non-sinusoidal trace and discontinuous trace.

d. Mount shells on packer;

e. Put impression number, side number and reference marks on Parafilm directly with a ball-point pen;

f. Assemble quick-coupling and self-aligning rods and place packer in desired location;

g. Select and record location of reference line for orientation;

h. Turn on gas pressure source (valve A);

i. Turn up regulator (valve B) until appropriate pressure is read in pressure gauge; record pressure (p);

j. Hold for desired time interval (typically 2 to 5 minutes); record actual time elapsed ($t_{inflate}$) between opening valve B and closing valve B (the next step);

k. Turn down regulator (valve B), or close valve A and disconnect at B for faster bleeding of pressure;

l. Wait until the packer completely deflates;

m. Retrieve packer;

n. Take impression records off shells and inspect their quality;

o. Roll and store impression records after inspection and field interpretation.

2. Analytical Procedure (Refer to Appendix 3, Table 4, Data Analysis Form and Fig. 11).

a. Lay impression records over base grid, with the corresponding reference marks overlapped.

For each fracture trace:

b. Read off β for each fracture trace; if hole size is not

NX, calculate $\beta$ by measuring $S_I$ and $S_{II}$;

c. Measure $L_I$ and $L_{II}$;

d. Calculate $\alpha$ by $\tan\alpha = \frac{\text{Diameter of Hole}}{L_I \sim L_{II}}$ ; it should be comparable to the value of $\alpha$ given by the sine curve which best matches the trace;

e. Calculate location of fracture, $D = N_1 + (L_I + L_{II})/2$;

f. Measure and record apparent aperture $e_a$; give minimum, maximum and average values if variation of aperture is great;

g. Calculate normal aperture from $e = e_a \sin\alpha$;

h. Plot the point $(\alpha, \beta)$ on a stereonet overlay (Fig. 14); this would be the upward normal to the fracture if the borehole is vertical and the reference line is located at the north pole;

i. Plot a point at the north pole, rotate the stereonet overlay about its center until that point coincides with the actual location of the reference line during the test;

j. Plot a point at the center, rotate the points on the overlay about a horizontal line perpendicular to the direction of the borehole axis until this points coincides with the point representing the borehole axis in its correct orientation. The point $(\alpha, \beta)$ now represents the correct upward normal to the fracture.

Steps h to j may be combined for fractures in a same borehole.

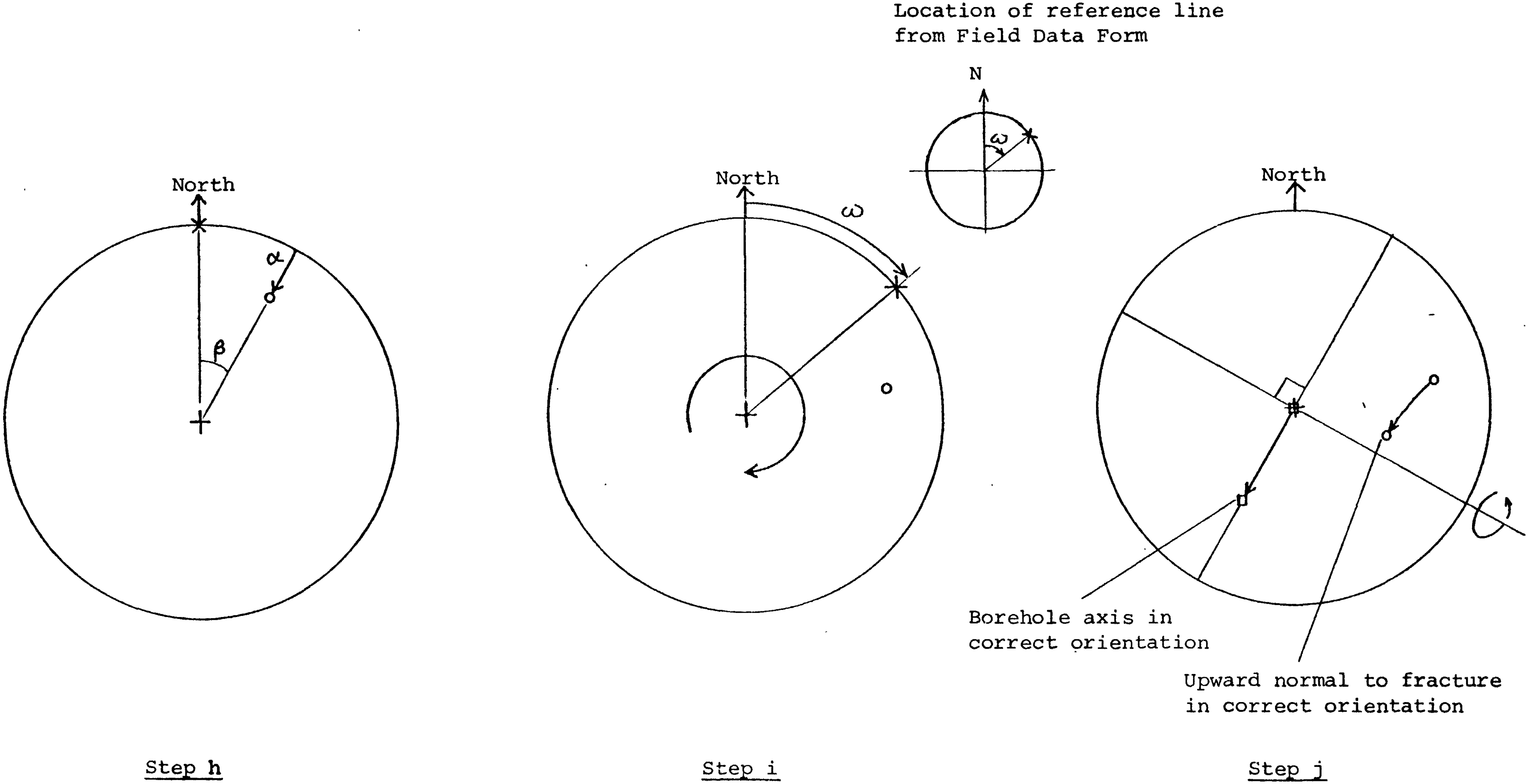



Figure 14. Absolute strike and dip from $\alpha$ and $\beta$ with a stereonet.
(Step numbers refer to Section D of Chapter II)

# III. Dilatometer

## A. Introduction

The Lynes SCI-PIP packer was received in early November 1979, delivery being delayed by production problems. It is 2-5/8 inches in diameter, too big to serve as the expanding packer for pressing the 1/4 inch thick impression shells onto NX boreholes. Specifications for impression packers and dilatometers may be incompatible: impression packers demand small diameter packers to allow for clearance (Fig. 15), while dilatometers demand packers with diameter close to that of the borehole to maximize pressure transfer (Fig. 16). Also, the Parafilm has to be replaced for every test, while dilatometer measurements may be taken continuously along a hole without retrieving the instrument. Furthermore, the impression shells might have to be taken off every time before making dilatometer tests to obtain complete radial pressurization and to avoid correcting for its compression.

The potential advantages gained by combining dilatometer and fracture mapping function in one instrument are strongly countered by the difficulties and limitations this invites. When this was appreciated, the direction of the research was turned toward developing two different instruments that may be employed in a complimentary manner by mounting in series on the same drill string or operating sequentially in one hole. This conclusion was strengthened when we learned from D. V. Hinds in December 1979, about a French steel-reinforced packer (Petrometalic Dilatable Hose) that is rated for a minimum of 600 bars (9,000 psi) working pressure in free air. This is comparable to the highest pressure

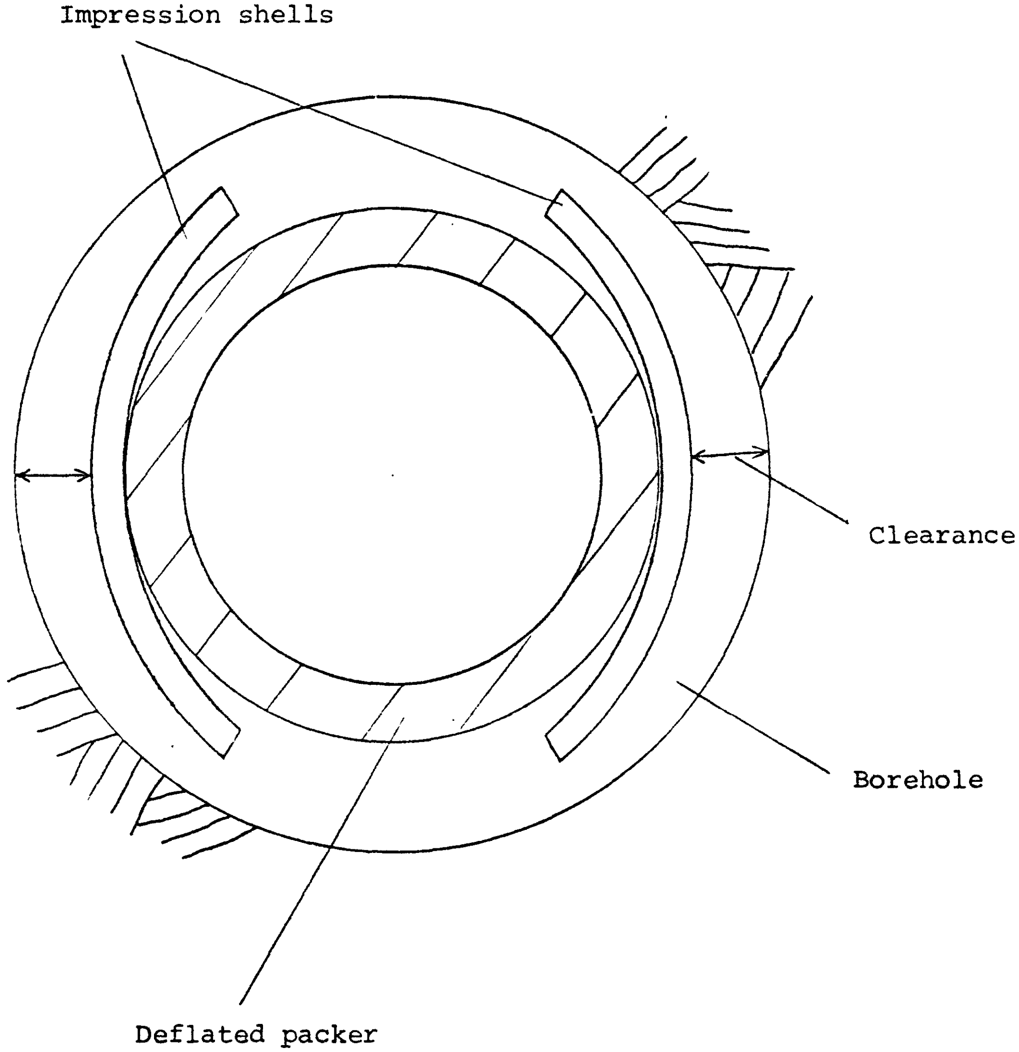



Figure 15. Clearance is desirable to avoid marring impressions.

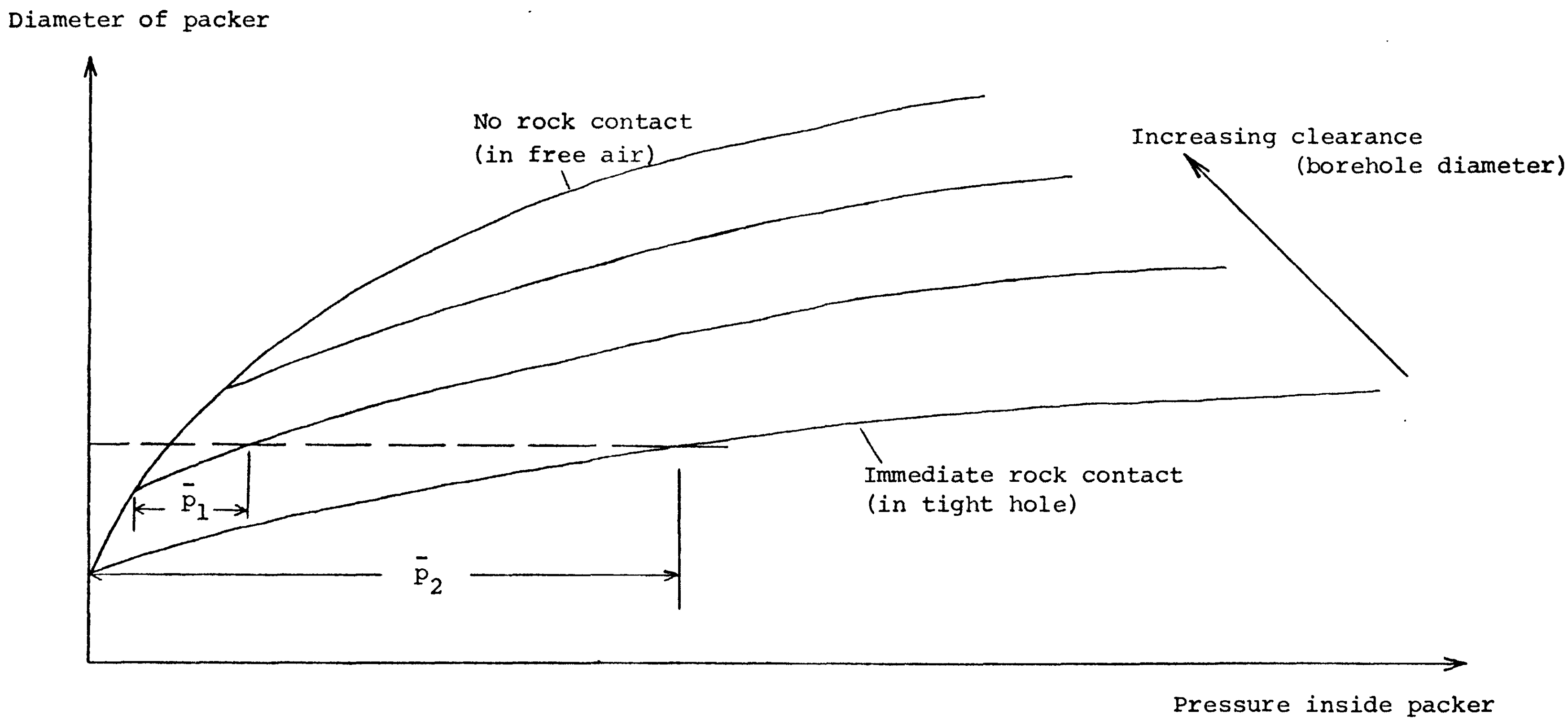



Figure 16. Typical load-deformation curves of packers. Pressure transferred onto the borehole walls ($\bar{p}$) decreases with increasing clearance.

available in existing dilatometers, but the length of the packer--and hence the volume of rock tested--could be considerably larger. A 39 mm diameter x 1 m length packer was ordered; it was received in mid April 1980, and has not yet been tested.

A literature review was performed to identify areas that need to be considered in design, construction, calibration, operation, and data interpretation of dilatometers. A wealth of information is available and the main points are summarized in the following discussion.

B. Major Considerations in Design, Construction, Calibration, Operation, and Data Interpretation

Dilatometers are defined as devices which apply radial hydraulic pressure to the free standing sides of boreholes and measure the corresponding deformations. About twenty types of dilatometers were encountered in the literature review, of which thirteen are described in Table 1.

There are two ways to measure deformation. The first measures the integrated effect of all diameters along the loaded length of the borehole by measuring the volume of fluid that goes in or out of the packer. The second approach measures changes in diameter at several points by electrical transducers (usually LVDT's). It is relatively simple to measure the volume change, no delicate and vulnerable electronics being necessary. The Menard Pressuremeter measures volume change from the water level in a clear plastic tabing, while the Cylindrical Pressure Cell and the Colorado School of Mines Cell achieve this by counting the number of turns on their screw pump pressure generators.

TABLE 1. SUMMARY OF INFORMATION ON DILATOMETERS

| Name of Device | Method of Pressure Application | Method of Measuring Deformation | Number of Diameters Measured | Diameter of Device (mm) | Diameter of Device (in) | Diameter of Borehole (mm) | Diameter of Borehole (in) | Length of Loaded[2] Area (mm) | Length of Loaded[2] Area (in) | Maximum Contact[3] Pressure (kPa) | Maximum Contact[3] Pressure (psi) | Packer Material | Special Features and Remarks | Country of Origin | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kogler Probe | Pump gas to expand cell | Volume change on expansion | Integrated effect of ell diameters along loaded length | 100 | 3.94 | | | 1250 | 49.2 | | | | First dilatometer. Technological and theoretical problems limited applications. | France (1930) | Kögler (1933)<br>Baguelin, et al. (1978) |
| Menard Pressuremeter E, G, GB | Gas pressure against water filling cell | Volume change on expansion | Integrated effect of all diameters along loaded length | 44<br>58 | 1.7<br>2.3 | 48<br>63 | 1.9<br>2.5 | 660<br>420 | 26.0<br>16.5 | 2,500<br>4,000<br>10,000 | 370<br>600<br>1,500 | Rubber | Guard cells and coaxial tubings. Considerable experience in soils. Continuous modifications. | France (1957) | Menard (1957)<br>Dixon (1970)<br>Baguelin, et al. (1978) |
| Cylindrical Pressure Cell (PC) | Pump glycerine with screw pump to expand cell | Volume change on expansion | Integrated effect of all diameters along loaded length | | | 38 | 1.5 | 203 | 8.0 | 69,000 | 10,000 | Copper membrane | Mapped fractures with copper sleeve | USA (1964) | Panek, et al. (1964) |
| [illegible] Dilatometer | Hand pump water to expand cell | 2 "MCH" instruments bearing on membrane | 2 | 200<br>300 | 7.9<br>11.8 | | | 1000<br>1200 | 39.4<br>47.2 | 4,100<br>6,900 | 600<br>1,000 | Rubber | | Yugoslavia (1964) | Kujundzic and Stojakovic (1964)<br>Kujundzic (1965) |
| Janod-Mermin Device | Pump oil to expand cell | 3 LVDT's | 3 | 164 | 6.5 | 168 | 6.6 | 770 | 30.3 | 15,000 | 2,200 | Aluminum | | France | Janod & Mermin (1964) |
| Comes' Cell | Pump oil to expand cell | 3 LVDT's | 3 | | | 160 | 6.3 | 1600 | 63.0 | 15,000 | 2,200 | | | France | Comes (1965) |
| LNEC Device | Hand pump water to expand cell | 8 LVDT's bearing on rock | 4 | 74 | 2.9 | 76 | 3.0 | 545 | 21.5 | 20,000 | 3,000 | Neoprene | Considered effect of fracturing rock around borehole during test. | Portugal | Rocha, et al. (1966)<br>Charrua-Graca (1974) |
| Tube Deformeter | Pump oil to expand cell | 24 LVDT's bearing on membrane | 4 | 297 | 11.7 | 300 | 11.8 | 1300 | 51.2 | 4,500 | 650 | Neoprene | | Japan | Takano (1966) |
| Pressiometer | Hand pump liquid to expand cell | Measuring probes bearing on rock | | | | 46<br>76 | 1.8<br>3.0 | 680 | 26.8 | 20,000 | 2,940 | Rubber | | USSR (1964-66) | Prigozhin (1968) |
| Geoprobe | Pump compressed gas to expand cell | Diametral change from longitudinal deflection of braided metal cover | Integrated effect of all diameters along loaded length | | | 48 | 1-7/8 | | | 10,000 | 1,500 | Rubber chamber covered by braided steel tubular | | Canada (?) (1966) | Geoprobe (1967) |
| Colorado School of Mines (CSM Cell) | Pump water/anti-freeze mixture with screw pump to expand cell | Volume change on expansion | Integrated effect of all diameter along loaded length | | | 38 | 1.5 | 165 | 6.5 | 69,000 | 10,000 | Adiprene membrane | Filled with glass beads to minimize fluid volume. Interpret results in terms of volume stiffness. | USA (1970-72) | Hustrulid (1975) |
| Elastmeter | Pump fluid to expand cell | 6 "Contact Balancers" bearing on membrane | Integrated effect of 3 diameters | 60 | 2.4 | | | 520 | 20.5 | 20,000 | 3,000 | Elastic rubber | | Japan | Ohyo, et al. (1975) |
| Coffey Pressuremeter PMX-20 | Hand pump oil to expand cell | 4 LVDT's bearing on membrane | Average over a section 110 mm x 10 mm | 70 | 2.8 | 76 | 3.0 | 400 | 15.8 | 20,000 | 3,000 | Flexible membrane | Primarily for measuring shear strength (up to 8 MPa) of weak to medium rocks. | Australia | Hughes (1978?)<br>Coffey & Partners (1978?) |

[1]Table enlarged from Goodman, Van, and Heuze (1970).
[2]The actual area of load is somewhat less because of unequal expansion.
[3]The numbers given are hydraulic line pressures at the elevation of the test. The actual contact pressure will be different due to membrane resistance and other system effects.

However, use of the volume-measurement approach requires a liquid system of known compressibility and volume or a field calibration procedure. In either case, leaks cannot be tolerated. On the other hand, measuring diametral changes by electronic devices downhole enables an appreciation of anisotropy, and the necessary electronics provide more precise data that may be recorded continuously and analyzed by computers. Either compressed gas or hand-pumped hydraulic fluid may be used to apply pressure in this system, and leaks are tolerable.

With LVDT's, large errors may arise in cases where the dilatometer moves up or down relative to the walls during expansion; Prigozhin (1968) described a "floating hanging" mechanism of the measuring unit to avoid such distortions. Inaccurate measurement may also occur when the gage points coincide with local inhomogeneities; measuring along several diameters should resolve this problem. Furthermore, the tolerance on borehole diameters is small due to limited travel of the electronic transducers.

On the whole, calibration and corrections are few and simple for the diameter-measuring approach. One of them is the membrane correction. Compression of the membrane has to be subtracted from the measured displacements unless the gage points are brought through the membrane against the rock. Another correction is the hydrostatic head which should be added to the pressure gage reading if the gage is located at the surface. The electronic transducers also require periodic calibration.

The volume-measuring approach, however, employs a variety of calibration and correction procedures. The pressure measurements should be corrected for membrane resistance in addition to hydrostatic head, and the volume measurements should be corrected for tubing expansion, membrane compression, fluid compression, effects of end-restraints and deviation from plane strain due to finite length of loaded area.

The Menard Pressuremeter uses coaxial tubings to minimize tubing expansion by surrounding the tubing that leads to the measuring cell with a concentric tubing that enters into guard cells. The guard cells above and below the measuring cell are incorporated in the Menard Pressuremeter to keep the latter from changing length and to create a stress field closer to plane strain along the middle measuring section. It may be mentioned here that plane strain conditions are assumed to exist at mid height for interpreting diameter-measuring dilatometers; the assumption is good when the load length exceeds four to five times the diameter, and is 6 R from the top or 2 R from the bottom of the hole (Likhovtsev, 1976).

There are several different schemes for calibrating and correcting dilatometer measurements. In the Menard Pressurementer system, volume calibration is achieved by expanding inside a thick-walled steel tube, while pressure calibration is achieved by expanding in free air. In the Cylindrical Pressure Cell system, expansion inside two different cylinders is used to obtain the constants relating $\Delta P/\Delta V$ as measured to $\Delta P/\Delta V$ of the borehole. The Colorado School of Mines Cell, modified from the Cylindrical Pressure Cell, makes use of at least one cylinder with known properties to measure the volume "stiffness" of the system; the volume stiffness of the rock mass tested could then be calculated and related to its modulus of rigidity. The relative merits of these schemes have yet to be compared.

In every calibration and subsequent testing, the total amount of fluid in the system should be kept constant. Temperature significantly affects measurement and should be held unchanged during calibration and between testing.

Water is used to expand the measuring cell, in the Menard Pressuremeter; glycerine is used in the Cylindrical Pressure Cell (for its low compressibility); a water/antifreeze mixture is used in the Colorado School of Mines Cell; and hydraulic oils are used by the other dilatometers. Pure water invites rusting of the metal parts, is more compressible than oil, requires de-airing, and has a higher freezing point; glycerine is highly viscous and flows very slowly.

To obtain accurate volume measurements, it is necessary to minimize the total amount of fluid in the system. The Colorado School of Mines Cell is filled with glass beads for this purpose.

Deflation of the dilatometer is required to allow relocation and retrieval of the instrument. Relief valves, internal pressure or vacuum are incorporated in some dilatometers to facilitate deflation especially in dry boreholes where no external pressure exists. Systems expanded with compressed gas are easier to deflate than those expanded with liquid.

Rough-walled holes pose a problem as to when contact between the probe and the borehole is complete; well drilled holes that do not collapse are preferred.

Local effects due to non-homogeneity, larger cracks, fissures and schistosity are more significant in tests performed in small diameter holes, since a smaller volume of rock is loaded. Early dilatometers had large diameters to offset these effects. However, more dilatometers are designed to operate in boreholes used in routine exploration. Probes designed for testing in smaller holes may also be used in slightly bigger holes with metal sleeves or cylinders over the probes (Geoprobe, 1967?).

C. Temporary Set Up (Preliminary Design)

In view of the considerations discussed above, we consider it more appropriate to study the various factors in detail before finalizing any design. However, a preliminary design proposed as a basis for modification is outlined below.

We have three different packers at the present for constructing dilatometers. Table 2 summarizes their characteristics. For simplicity of construction, the volume-measuring approach for measuring deformation will be used; the diameter-measuring approach may be incorporated later to allow investigation of anisotropy, but construction and operational problems as mentioned before will have to be surmounted.

An Enerpac Hydraulic Hand Pump and a High Pressure Equipment Pressure Generator (manually operated piston screw pump) have been secured for applying pressure up to 10,000 psi. The Lynes packer, the Petrometalic packer, the hand pump and the screw pump are shown in Fig. 17. The hand pump, to be equipped with an external reservoir, will inject the fluid until contact between the dilatometer and the borehole wall is complete; the screw pump will carry on the expansion for more accurate measurements. Volume measurement is accomplished by

Figure 17. From left: Lynes SCI-PIP packer, High Pressure Equipment Pressure Generator, Enerpac Hydraulic Hand Pump, and Petrometalic packer.

counting number of strokes of the hand pump and number of turns of the screw pump; a vernier is being purchased for more precise reading from the latter.

Either hydraulic oil, glycerine or water/antifreeze mixture may be chosen as the pressurizing fluid for the Ductube and the Lynes packer; but use of oil is not compatible with the Petrometalic packer, while the Enerpac Co. advises the use of hydraulic oil for its hand pumps. The choice will be made after contacts with the manufacturers and studies concerning the effects of viscosity and compressibility of the fluids.

The Lynes packer is well suited for testing in NX holes; the ductube, due to end grips of 2-1/2 inches diameter, will have to be used in NX holes. The Petrometalic packer is designed to pack off 45 mm diameter holes which are standard only in Europe; holes drilled with special bits of 41 to 45 mm diameter will be required for this packer.

The calibration scheme will follow either that of the Menard pressuremeter or the Colorado School of Mines Cell; both schemes utilize metal cylinder(s) and two are being made, equipped with strain gauges, to permit an evaluation of the relative merits of these schemes.

Glass beads will be placed inside the packers to minimize the total amount of fluid in the system and hence their compressibility. This is especially important for the ductube owing to the large radial expansion it has to undergo to meet the borehole walls.

Deflation of the packers will hopefully be achieved by opening the valve in the hand pump. In case the membrane contraction is insufficient to deflate the packer, a reverse pumping mechanism will be designed. At the present, we do not foresee incorporating guard cells and coaxial tubings into the system, although they may be considered if it is found that their use leads to significant improvements. Metal sleeves covering the probe for protection or testing in slightly oversized holes may also be added at a later stage. A disc to keep pieces of rocks from falling into the hole and jamming between the packer and the hole will be designed, in addition to borehole guides which house the pressure connections and the connection to the drill string. The borehole guides will also be designed to fit into a fishing tool for retrieving the instrument in an emergency. High precision pressure gauges and length of high pressure tubings will be purchased. A schematic drawing of the preliminary design is shown in Fig. 18.

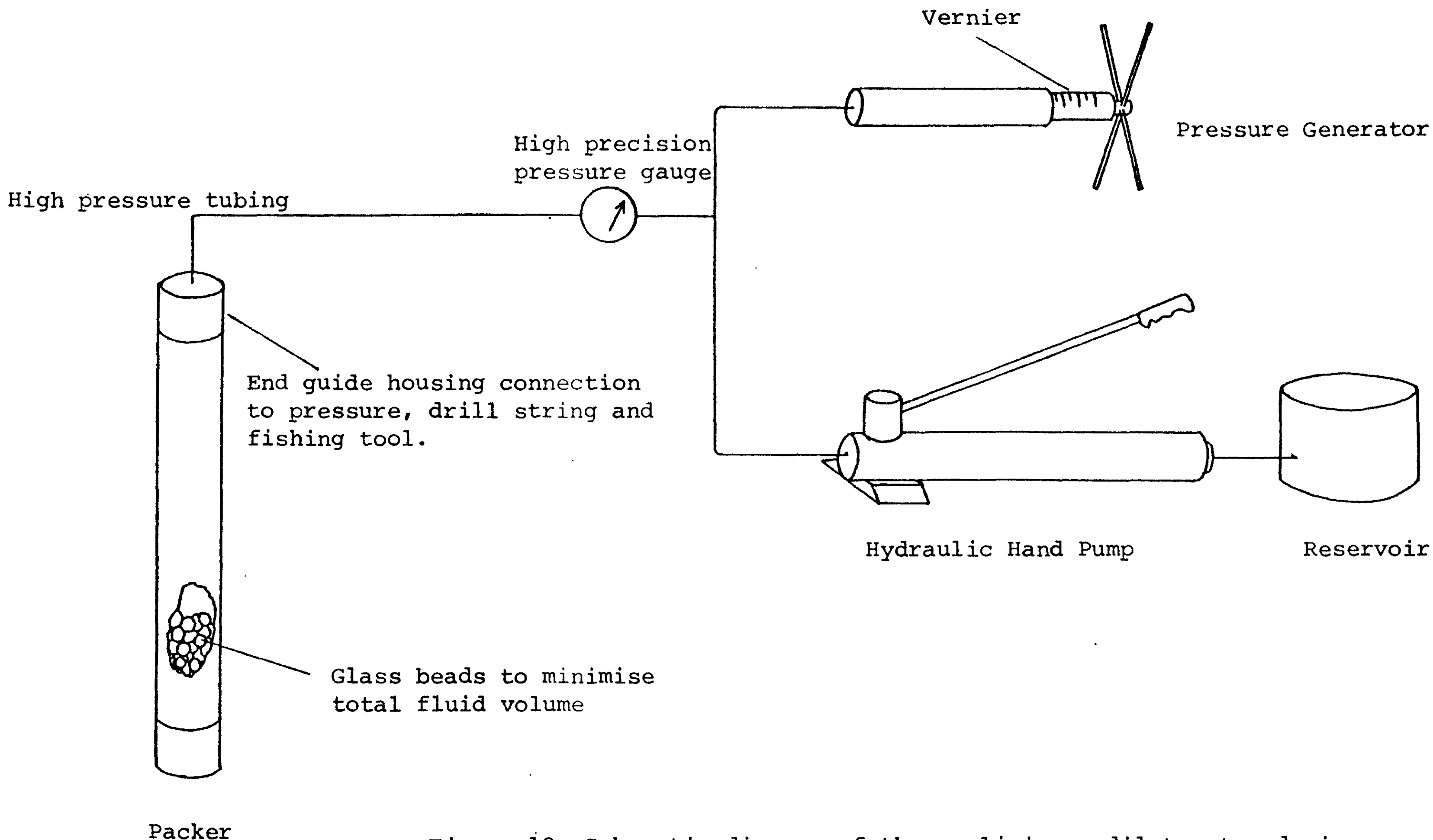



Figure 18. Schematic diagram of the preliminary dilatometer design.

TABLE 2

CHARACTERISTICS OF PACKERS ACQUIRED FOR BUILDING THE DILATOMETER

| Name of Packer | Diameter of | | Exterior Diameter Under Maximum Working Pressure | Length | Maximum Working Pressure | Reinforcement |
|---|---|---|---|---|---|---|
| | Packer | Borehole | | | | |
| Ductube (High Pressure Impression Packer) | 2-1/8" | 3" | | 27" | 500 psi | Fiber Reinforced Rubber |
| Lynes Packer (SCI-PIP) | 2-5/8" | 3" | | 36" | 4,500 psi | |
| Petrometalic Packer (BIMBAR 6) | 39 mm | 41-45 mm | 48 mm | 1 m | >9,000 psi | Steel Reinforced Rubber |

# IV. Conclusions

## A. Impression Packer

The impression packer described in this report is a potentially valuable tool for locating and describing fractures, distinguishing real fractures from core breaks, and other hole logging functions. It seems to be especially suitable for hydrologic studies where information can be obtained on fracture apertures and for weighing the respective influences of different joint sets. It is less expensive, more accurate, simpler to use and less time-consuming than previously available impression packers, especially after improvements made during this research.

However, there are limitations to its application that have yet to be evaluated more carefully. These include the minimum aperture of fractures needed for good impressions with attainable pressures and reasonable pressurized durations, the effect of drilling and joint filling on the accuracy of results, the precision with which the measurements can be made, and the adequacy of representing fractures which may be discontinuous and non-planar by their traces of intersection with a borehole.

Also, studies still have to be performed on image enhancement, other impression materials, downhole orientation, protection from rupture and jamming of instrument, and other practical procedures.

Background textures have shown up in shale (Hinds, 1974) and sandstones, but not in granite (Chan and Goodman, 1980). The ability of the impression packer to recognize rock types is yet uncertain.

The impression packer method of fracture mapping is a line sampling method as opposed to fracture mapping over an area such as outcrops or faces of tunnels and adits. Statistical treatment appropriate to this method should be applied to the results. Terzaghi's (1965) correction is an example; more research is required in this respect.

B. Dilatometer

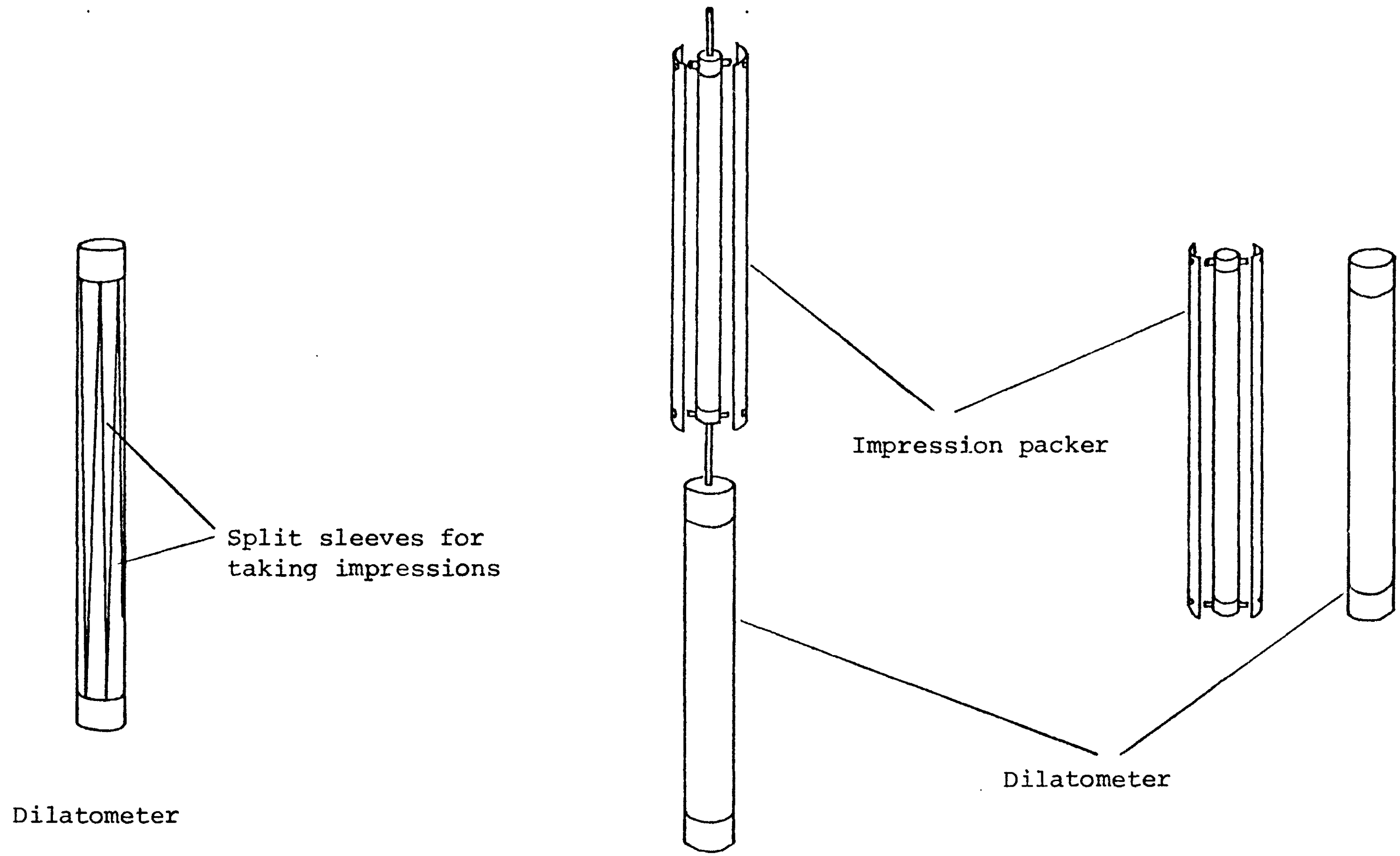
The pressure that will be exerted by our new dilatometer exceeds those of existing devices of comparable length, and its length will be considerably larger than those of existing devices with comparable pressure limits. Its high pressure capacity enables more comprehensive tests and better accuracy, and the rock may even be broken to yield information on strength and stress; the larger length means that a bigger volume of rock is included in each test.

Design details, calibration procedures and loading patterns of existing dilatometers will be carefully compared and the best incorporated into this new design. The effects of drilling on the rock and stress field around boreholes will have to be evaluated; for example, Rocha (1969) suggested that dilatometric modulus might be higher than those measured from surface loading due to stress concentration around boreholes, but Charrua-Graća (1979) reported the opposite, Also, the interpretation of results with respect to strength and stresses need to be studied. The Pressuremeter provides information on both when used in soils and soft rocks; for hard rocks, theory developed by Ladanyi (1967) shows that ultimate borehole radial pressure is 6 to 10 times the unconfined compressive strength of the rock and depends on strength parameters, deformability parameters, and initial stress. It is also of interest to examine the data obtained by the various dilatometers to assess their relative merits, and to correlate them to values measured by other methods.

C. Impression Dilatometer

The effect of rock fracturing on the modulus of elasticity recorded by a dilatometer was considered by Rocha (1969). Mapping the fractures before and after performing a dilatometer test would enable a more accurate appraisal of the occurrence of induced fractures and also the correct formula to use for interpretation. This is a main interest in this research project. To do this, three approaches are possible: simultaneous measurement of fractures and deformability with one instrument (single-journey), simultaneous measurement of fractures and deformability with an impression packer and a dilatometer connected in series on one drill string (multi-component) and sequential insertion of an impression packer and a dilatometer (Fig. 19). The last approach is feasible insofar as the necessary instruments are available, the dilatometer could be the impression packer with the impression shells removed. A model high pressure impression packer has been assembled and might be used to obtain fracture traces at different pressure levels and to serve as a dilatometer in soft rock with the necessary accessories (Fig. 20).

The idea of combining the impression packer and the dilatometer into one impression dilatometer (the first approach) was an effort to




(a) Simultaneous : single journey (b) Simultaneous : multi-component (c) Sequential insertion

Figure 19. Three approaches to combining fracture mapping with dilatometer testing.

Figure 20. A model high pressure impression packer. Three rubber bands were used to tie Parafilm down on the front shell.

shorten and simplify the operation; the Cylindrical Pressure Cell could be called a primitive impression dilatometer since fractures were mapped on its copper sleeves and verified by borescope (Panek, 1970). Impression shells or split metal sleeves may also be put onto a dilatometer to allow impression and deformability data to be taken simultaneously; the radial pressure is not complete and volume corrections due to compression of shells or sleeves will have to be made. However, these are essentially still dilatometers with an impression-taking capability which when utilized will necessitate the instrument to be taken out of the hole after each test to retrieve the fracture information.

With the impression packer and dilatometer we have, the second approach, which is to put the two instruments in series on one drill string, is still an improvement over the third approach; one journey down the hole is enough instead of two needed in the sequential insertion for each test, but there are practical problems that need to be surmounted before the multi-component device could be used.

In any case, how to combine the fracture information into the interpretation of the load-deformation data is a topic that requires further investigation.

D. General Conclusions

It should be noted that although the instruments described were intended for inspecting foundations and abutments of old dams, the fracture and deformability information that they can provide are also of interest to exploration for rock slopes (e.g., open pit mines, highway cuts, spillway cuts), tunnels and underground openings, groundwater hydrology, tall buildings, pressure conduits, arch and gravity dams, and stress measurements, just to name a few.

Also, even though the choice of a downhole instrument was dictated by the original problem (namely, inspection of old dams), it has many advantages in any project in general. The main ones are that they are in-situ tests, can reach large depth or under water, are inexpensive and hence may be used to establish zones and perform statistical analysis. This is important since the analysis of stresses in a rock mass is sensitive not only to "the value" of the deformation modulus of the rock, but also to the distribution of deformability values in the foundation. However, an advantage is an advantage only when it is realized, and that means in this case a conscious effort for more investigation on statistical interpretation of the results. Drill holes are usually available as part of every exploration, and they provide a less disturbed site for testing than exposed surfaces or adits. However, the volume of rock tested is still rather small (several cubic feet) (Heuze, 1980), the traces of the fractures mapped are very limited in extent, the effect of drilling on the fracture traces and deformability may be significant in some cases.

E. Upcoming Activities

Research will continue in theoretical analysis, laboratory testing and field testing as mentioned previously. We have started drilling at a quarry in Marin County (Fig. 21) which will provide an excellent field site for future studies; more tests will be conducted in the Stripa core, and we plan to try the instruments out at actual

Figure 21. The assembled drill rig at a greywacke quarry in Marin County.

engineering sites when circumstances allow. Contacts with experienced investigators as well as collaboration with researchers in the same field will be made a part of the future efforts. An additional point to be aware of is the kind of information needed by analysis and design procedures. For example, weak to medium rocks are more troublesome than hard rocks, hence measuring the modulus of the former is of more interest; "index" values of deformability may be enough for locating critically stressed areas whereas "design" values would be needed for settlement calculations (Norrish, 1974). The applications should be kept in mind in the course of designing the instruments so that they would be best suited for those specific purposes.

# PART 2--CREEP MONITORING

## I. Summary of Activities

A method was developed and demonstrated for surface creep monitoring on hillslopes using a linear variable differential transformer (LVDT) attached to an anchored INVAR wire. The greater part of this phase of the research project was reported upon in the Annual Report of January 1979, and will not be reproduced herein.

Wire of 0.024 inch (0.61 mm) diameter was stretched in hillslope traverses with lengths of 40-140 feet on both actively creeping and stable slopes. A wire is anchored at one end to an adjustable LVDT housing connected to a Rustrak recorder. The recorder has been modified to run continuously for three weeks (500 hours) on an 18 volt battery combination. The recorder is capable of a wide range of recording sensitivity, variant with the geological conditions at any particular site. Traditional problems with low-amplitude recording have been surmounted by employing the results of a series of calibration studies and operational procedures producing corrections for temperature elongation and wire sag. It is felt that low-amplitude environmental effects have been accounted for very thoroughly.

Operating on hillsides with low-amplitude creep movement has required a longer baseline for meaningful study. In all cases it has been found prudent to take measurements in 24-hour intervals during early morning hours (midnight to 4 a.m.) when near identical temperatures necessitates smaller temperature corrections.

Four principal sites have been investigated in the past two years for varying intervals of continuous measurement. These are located at: Moraga, California (312 hours); Orinda, California (1,176 hours); Chair Mountain Landslide, Colorado (96 hours); and Congress Springs Landslide, Saratoga, California (500 hours)*.

Wire length between shallow ground anchors at these sites varied from 43 to 126 feet (13.1 to 38.4 meters). At the Moraga and Orinda sites one LVDT-INVAR wire measuring trace was placed on a supposedly failing slope while the other trace was on an adjacent slope of similar steepness, but showing no visible signs of downhill movement. This was done to compare values between normal surficial downslope creep rates and accelerated rates measured on a slope in a state of incipient failure. Creep rates ranged between $3.0 \times 10^{-6}$ inches/hr ($7.6 \times 10^{-6}$ mm/hr) and at least $3.6 \times 10^{-3}$ inches/hr ($9.2 \times 10^{-3}$ mm/hr). Creep rates on slopes undergoing non-slide-related (natural) downslope creep movement were found to be less than $1 \times 10^{-4}$ inches/hr ($2.54 \times 10^{-4}$ mm/hr). Data from the two large landslide masses instrumented at Chair Mountain and at Congress Springs suggests that creep rates above the latter value are associated with active sliding.

The division between active and inactive was made on the basis of careful field observations and geological mapping. The range in values

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*Measurement in progress.

can be ascribed to several factors including: physical properties of the slope materials; seasonal variations in moisture content; and the slopes' present state of equilibrium (it was found that an already failure or slumped earth mass tends not to creep after a major movement).

## II. Conclusions

1. Hillslope creep rates have been observed with a rate of 0.001 inches/hr ($2.54 \times 10^{-4}$ mm/hr) documented as an appropriate boundary between natural creep and accelerated creep associated with failure. This threshold value is in general concurrence with previous studies dealing with natural slope creep such as that of Fleming (1972).

2. Another discovery is that all of the slopes monitored move in a regular jerky fashion, i.e., representing a "stick-slip" form of shear failure. This mode of movement suggests a dynamic system where re-equilibration of the slope takes place after each tiny pulse of movement

3. Inherent in this system of measurement is the cognizance of the anchor positions and the geometry of relative motion between them relative to the vectors of geologic motion. At the Chair Mountain and Congress Spring landslide sites, back-to-back trace arrays were emplaced across series of horst/graben and tension features of actively failing earth masses. In one case a set of anchors was placed within a pseudo-stable block of a larger rotating slide mass and, therefore, recorded little movement.

4. The creep measuring system has shown that it can detect

state-of-activity of a failing slope much as a microseismic program is presently used to detect potential fault activity. Confidence in these low-amplitude measurements requires a time base line for instrumentation. The time interval of the required base line is dependent on the rate at which the slope creeps; which in turn is dependent on the slope geology, seasonal hydrologic regime, and geometrical set-up of the anchors.

5. It is generally assumed that slopes that are actively experiencing accelerated creep movement may be very susceptible to catastrophic failure due to seismic loading. This is due to several combining factors including the following. Shear strength of cohesive materials may be reduced by pore pressure increases. An actively advancing slide mass usually possesses dilatant zones where the intact rock mass fabric is brecciated and separated, thereby reducing internal friction and cohesion. A crown scarp with already-developed tensile separations will possess little cohesion and will act as avenues for strength-decreasing hydraulic forces. Continual downhill motion produces cataclastic zones of crushed material that possess residual shear strengths of the parent rock mass. One could infer, therefore, that the older and more active a slide mass is, the less its resistance is to seismic triggering. Both of the larger slide masses instrumented may have been seismically induced because large lacustrine alluvial accumulations lie upstream of their dissected toes. This indicates sudden damming of water courses.

6. The future in microcreep measurement lies in the gathering of more base line data. Additional experiments and instrumentation are

ongoing in the Coast Ranges area to attempt further establishment of "threshold" creep values so that short duration base line results can be viewed more definitively. The future employment of multi-channelled and telemetry-based recording systems is being explored. Other major slide masses of great potential disaster significance, such as Congress Springs in Saratoga, are being monitored with long-term base lines and complete temperature recording.

## REFERENCES

Anderson, G. W. (1976) "Impression tool evaluates perforation effectiveness," World Oil, May.

Anderson, T. O. and Stahl, E. (1967) "A study of induced fracturing using an instrumental approach," Journal of Petroleum Technology, February, pp. 261-267.

Baguelin, F., Jézéquel, J. F., and Shields, D. H. (1978) The Pressuremeter and Foundation Engineering, Trans. Tech. Publications.

Barr, M. V. and Hocking, G. (1976) "Borehole structural logging employing a pneumatically inflatable impression packer," Proceedings of the Symposium on Exploration for Rock Engineering, Johannesburg, V. 1, pp. 29-34.

Brown, E. T., Harper, T. R. and Hinds, D. V. (1979) "Discontinuity measurement using the borehole impression probe, a case study," Proceedings of the 4th Congress of ISRM, Montreux, Vol. 2.

Chan, L. Y. and Goodman, R. E. (1980) "Report on field work with a new impression packer," Attachment to Twelve Month Technical Report to U.S.G.S. on Research Grant Number 14-08-0001-17761, February.

Charrua-Graća, J. G. (1974) Estudo de deformabilidade dos macicos rochosos com dilatometro, LNEC.

Charrua-Graća, J. G. (1979) "Dilometer tests in the study of the deformability of rock masses," Proceedings of the 4th Conference ISRM, Vol. 2, pp. 73-76.

Coffey and Partners Pty. Ltd. (1978?) "In-Situ Testing with Pressuremeters."

Comes, G. (1965) "Contribution a la détermination des caratéristiques mechaniques d'une foundation Rocheuse," Travaux, November.

Dixon, S. J. (1970) "Pressuremeter testing of soft bedrock," ASTM STP 477, pp. 126-136.

Fleming, R. W. (1972) "Soil creep in vicinity of Stanford University," Ph.D. Dissertation, Department of Geology, Stanford University.

Fraser, C. D. and Pettitt, B. E. (1962) "Results of a field test to determine the type and orientation of a hydraulically induced formation fracture," Journal of Petroleum Technology, May, pp. 463-466.

Geoprobe Instrument (1967) Literature by Testlab Corp.

Goodman, R. E., Tran, K. V. and Heuzé, F. E. (1970) "Measurement of rock deformability in boreholes," Proceedings of the 19th Symposium on Rock Mechanics, Austin, Texas, pp. 523-555.

Haimson, B. C. (1978) "The hydrofracturing stress measuring method and recent field results," Int. J. Rock Mech. Min. Sci., Vol. 15, No. 4, pp. 167-178.

Harper, T. R. and Hinds, D. V. (1978) "The impression packer: a tool for discovery of rock mass fracture geometry," Storage in Excavated Rock Caverns, Rockstore 77, Vol. 2, pp. 45-50.

Heuzé, F. E. (1980) "Scale effects in the determination or rock mass strength and deformability," Rock Mechanics, Vol. 12, No. 3-4, pp. 167-192.

Hinds, D. V. (1974) "A method of taking an impression of a borehole wall," Rock Mechanics Research Report No. 34, Imperial College, London.

Hughes, J. M. D. (1978?) "Development of a high pressure pressuremeter for determining the engineering properties of soft to medium strength rocks," Coffey & Partners, Sydney.

Hustrulid, W. (1975) "The CSM cell--a borehole device for determining the modulus of rigidity of rock," Proceedings of the 15th Symposium on Rock Mechanics, pp. 181-224.

Hutchinson, S. O. (1974) "Impression tool defines downhole equipment problems," World Oil, November.

Janod, A. and Mermin, P. (1964) "La Mesure des Caractéristiques des Roches en Place a l'Aide du Dilatométre a Vérin Cylindrique," Travaux, July.

Kogler, F. (1933) Bangrundprüfung im Bohrlock, Der Bauingenier, Berlin, Heft 19-20.

Kujundzic, B. (1965) "Experimental research into mechanical characteristics of rock masses in Yugoslavia," International Journal of Rock Mechanics and Mining Sciences, Vol. 2, pp. 75-91.

Kujundzic, B. and Stojakavic, M. (1964) "A contribution of experimental investigation of changes of mechanical characteristics of rock massives as a function of depth," Transactions of the 8th Congress on Large Dams, Edinburgh, Great Britain, pp. 1051-1067.

Ladanyi, B. (1967) "Expansion of cavities in brittle media," Int. J. Rock Mech. Min. Sci., Vol. 4, pp. 301-328.

Likhovtsev, V. M. (1976) "The effect of hole bottom on the results of pressiometric tests," SMFE, Vol. 13, pp. 268-269.

Menard, L. (1957) "Measures in-situ des propiétés physiques des sols," Annales des Ponts et Chaussées, No. 3.

Mitchell, J. K., Guzikowski, F. and Villet, W. (1978) "The measurement of soil properties in-situ," LBL-6363.

Norrish, N. I. (1974) "A comparison of three techniques for the determination of deformation properties of rock," M.S. Thesis, Department of Mineral Engineering, University of British Columbia.

Ohyo, S., Ogura, K. and Tsuji, M. (1975) "The instrument of new type dilatometer 'elastmeter' for studying the rock mechanics," Oyo Technical Note TN-06, Oyo Corporation, Tokyo, Japan.

Panek, L. A., Hornsey, E. E. and Lappi, R. L. (1964) "Determination of the modulus of rigidity of rock by explaining a cylindrical pressure cell in a drill hole," Proceedings of the 6th Symposium on Rock Mechanics, Rolla 64, pp. 427-449.

Panek, L. A. (1970) "Effect of rock fracturing on the modulus as determined by borehole dilation tests," Proceedings 2nd Congress, International Society for Rock Mechanics, Belgrade, Yugoslavia, No. 2-16.

Pentz (1980) Private communication.

Prigozhin, E. S. (1968) "New designs of pressiometer for rock massif stress-strain modulus definition," International Symposium on Rock Mechanics, Madrid, pp. 79-81.

Rocha, M. et al. (1966) "Determination of the deformability of rock masses along boreholes," Proceedings of the 1st Conference of the International Society of Rock Mechanics, Vol. 1, pp. 697-703.

Rocha, M. (1969) "New techniques in deformability testing of in-situ rock masses," ASTM STP 477, pp. 37-57.

Takano, M. and Shidomoto, Y. (1966) "Deformation test on mudstone enclosed in a foundation by means of tube deformation," Proceedings of 1st Congress of the International Society of Rock Mechanics, Vol. 1, pp. 761-764.

Terzaghi, R. D. (1965) "Sources of error in joint surveys," Geotechnique, Vol. 15, pp. 287-304.

Thorpe, R., Ralph, B., Watkins, D. and Hsu, R. (1980) "Preliminary fluid flow studies of the ultra-large stripa core," Technical Memorandum No. 69, Lawrence Berkeley Laboratory.

Thorpe, R., Watkins, D. and Ralph, B. (1979) "Sample preparation and fracture characterization: ultra-large stripa core," Technical Memorandum No. 51, Lawrence Berkeley Laboratory.

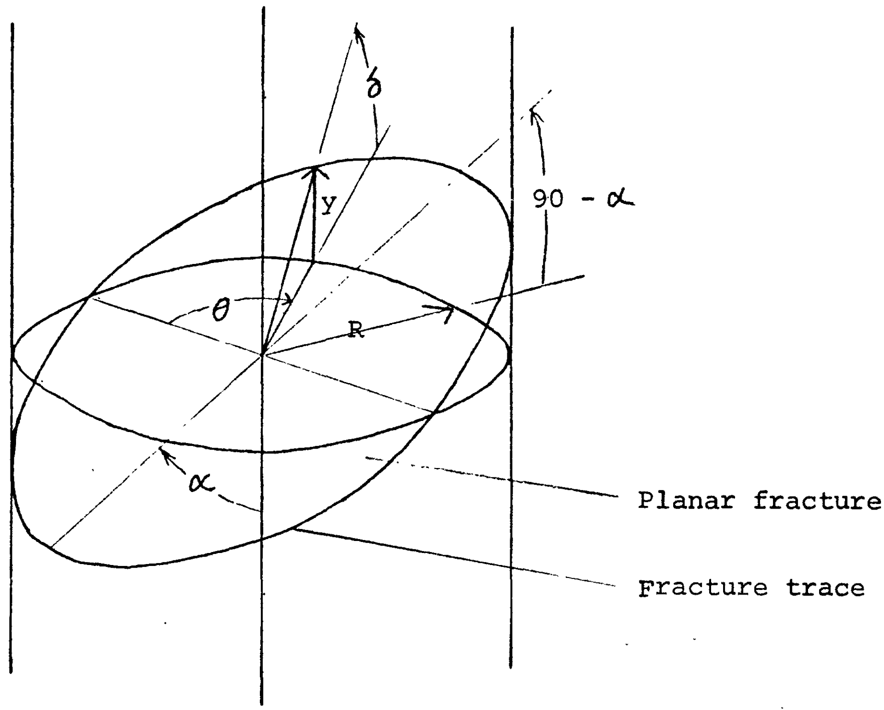
## APPENDIX 1. SINUSOIDAL SHAPE OF PLANAR FRACTURE TRACE ON IMPRESSION RECORD

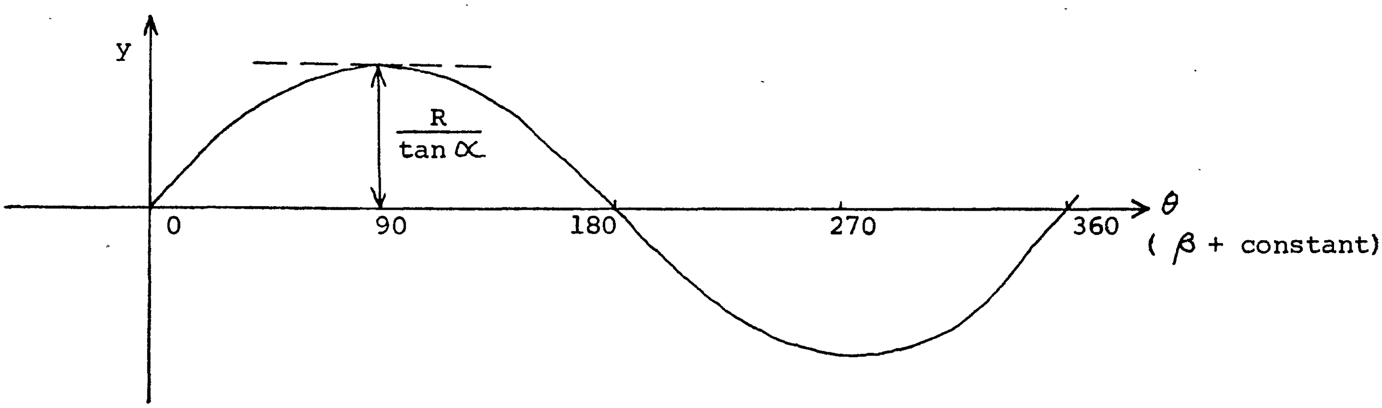
$$y = R \tan \delta$$

but $\tan \delta = \tan(90 - \alpha) \sin \theta$ (Apparent dip equation)

$$= \frac{\sin \theta}{\tan \alpha}$$

$$y = \frac{R \sin \theta}{\tan \alpha}$$



APPENDIX 2. TABLE 3--FIELD DATA FORM

## FIELD DATA FORM

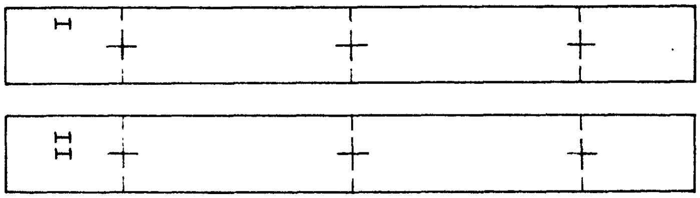
| | | | | | | |
|---|---|---|---|---|---|---|
| Project | | | | | | |
| Engineer | | | | | Date | |
| Boring Number | | | Location | | | |
| Size | | | Drill Bit | | | |
| Direction | | | Inclination | | | |
| Impression Number | | | | | | |
| Nomimal coverage | $N_1$ | | | | | |
| | $N_2$ | | | | | |
| Location of reference line | | N | N | N | N | N |
| Pressure (p) | | | | | | |
| Duration ($t_{inflate}$) | | | | | | |
| Remarks | | | | | | |
| Sketch of impression record | | II I | II I | II I | II I | II I |

APPENDIX 3. TABLE 4 -- DATA ANALYSIS FORM

DATA ANALYSIS FORM

| | | | |
|---|---|---|---|
| Project | | | |
| Engineer | | Date | |
| Boring - Impression No. | | Hole size | |
| Nominal coverage | $N_1$ | Number of fracture traces | I |
| | $N_2$ | | II |

Sketch of impression record




| Fracture No. | | | | | | |
|---|---|---|---|---|---|---|
| Side | I | II | I | II | I | II |
| $\beta$ (from grid) | | | | | | |
| S | | | | | | |
| $\beta$ (from S) | | | | | | |
| L | | | | | | |
| $(L_I+L_{II})/2$ | | | | | | |
| $A = L_I \sim L_{II}$ | | | | | | |
| $\alpha = \tan^{-1}(\frac{d}{A})$ | | | | | | |
| $\alpha$ (from stand. trace) | | | | | | |
| $D=N_1+\frac{L_I+L_{II}}{2}$ | | | | | | |

| | Max. | Min. | Avg. | Max. | Min. | Avg. | Max. | Min. | Avg. |
|---|---|---|---|---|---|---|---|---|---|
| Apparent aperture $e_a$ | | | | | | | | | |
| Aperture $e=e_a \sin\alpha$ | | | | | | | | | |

| | | | |
|---|---|---|---|
| Remarks | | | |

## APPENDIX 4. LIST OF VENDORS

| | |
|---|---|
| Ductube | Ductube Co. Ltd.<br>Daneshill Road<br>Lound,<br>Retford, Notts., U.K. |
| Enerpac Hydraulic Hand Pump | Enerpac<br>Butler, Wisconsin 53007, U.S.A.<br>Division of Applied Power Inc. |
| Lynes (SCI-PIP) Packer | Lynes Inc.<br>P.O. Box 12486, 8787 Tallyho<br>Houston, Texas 77017, U.S.A. |
| P.V.C. Foam | Vito Self Adhesive Ltd.<br>Hardwick Industrial Estate<br>Kings Lynn, Norfolk, U.K. |
| Parafilm 'M' | The American Can Company<br>International Operations<br>American Lane<br>Greenwich, Connecticut 06830, U.S.A. |
| Petrometalic Packer | Petrometalic<br>59405 CAMBRAI CEDEX<br>106, avenue du Cateau<br>Boite Postale 37, France |
| Pressure Generator | High Pressure Equipment Co., Inc.<br>1222 Linden Avenue<br>Erie, Pennsylvania 16505, U.S.A. |

APPENDIX 5. PARAFILM IMPRESSION MATERIAL