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An Integrated Testing Capability for In-Situ Stress Measurement and Determination of Reservoir Parameters

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Summary The history of the development of an integrated approach to stress measurement and reservoir testing in Australia is presented. The rationales and equipment/testing procedures involved in both cases are discussed from the viewpoint of the individual applications and their inter-relationship. Examples drawn from civil and mining engineering, as well as the oil and gas industry, are used to illustrate these points. A case is made for the cost effectiveness offered by the adoption of an integrated approach wherever applicable. The prospects for developing an understanding of the inter-dependence of permeability and stress is presented.

1. INTRODUCTION

Many problems in geomechanics require an understanding of the in-situ stress field as input to the design process. Much effort has been dedicated over the years to the development and application of stress measurement techniques. The introduction of hydraulic fracture stress measurement to Australia some fifteen years ago opened up the prospect of conducting stress measurements in deeper holes drilled from the surface as well as in the traditionally shorter holes drilled from underground. Over the last fifteen years a range of technology has been developed and a wealth of experience gained in the conduct of hydraulic fracture stress measurements in a range of geological conditions.

In more recent times, some of the technology developed for hydraulic fracture stress measurement has found application in the conduct of reservoir tests designed to determine critical parameters required for assessment of the hydrological performance of rock units.

This paper describes some of the advances made by the authors during the last fifteen years for both stress measurements and reservoir testing. The advantages of an integrated approach to stress and reservoir testing are discussed and experience from a range of project applications presented to illustrate particular aspects. Examples are presented from mining, civil engineering and the oil and gas industry.

2. STRESS AND PERMEABILITY MEASUREMENT

2.1 Stress

In the authors' experience two approaches to stress measurement have been developed:

- Hydraulic fracture stress measurement, well documented in the literature and capable, under favourable circumstances, of producing a complete estimate of the orientation and magnitude of the secondary stress field in the plane normal to a test hole axis.

Hydraulic fracture stress measurement has developed out of the geotechnical engineering environment in response to the specific need for detailed design information. The technique has some theoretical limitations and, like most other geotechnical testing methods, can be constrained by the prevailing rock conditions. Fundamentally, however, there is no in-built compromise inherent with regard to the information that can potentially be obtained. The theoretical basis for the technique, test procedures and approaches to analysis are comprehensively documented in Enever (1993).

- Step rate testing, aimed at providing an estimate of the magnitude of the minimum stress component existing in a fractured rock mass, remote from the test hole. This technique has been used by the oil and gas industry for some time to assess the minimum stress magnitude in relation to well stimulation design, and has parallels in hydraulic jacking tests used in civil engineering for assessment of water leakage potential from pressure tunnels.

Step rate testing has evolved as a testing procedure from the simple premise that in a fractured rock mass, injected fluid (usually water) will permeate along the fracture planes and prise open fractures oriented normal to the minimum stress component in the rock mass, providing such a fracture exists, causing a sudden increase in flow rate. By plotting flow rate against corresponding equilibrium pressure for a series of incrementally
increasing injection flow rates, the minimum stress magnitude can be estimated from the knee in the curve when the critical opening up occurs.

2.2 Permeability
The geotechnical industry has long conducted simple tests to assess the relative "tightness" or otherwise of fracture systems in boreholes. The industry has, however, generally embraced the more rigorous procedures used in groundwater and petroleum testing to assess far field (i.e. remote from the test hole) permeability, of matrix and/or fracture origin. Over recent years the authors have adapted the down hole tools and associated surface equipment used for hydraulic fracturing/step rate testing to allow the conduct of injection and/or production tests, following the procedures developed for well testing in the petroleum and groundwater industries, to rigorously measure permeability:

- **Injection testing**, as the name implies, involves injecting fluid at a constant rate into an isolated test interval for an extended period, followed by a period during which pressure decay is monitored in the isolated test interval after a down hole valve is actuated to seal the test horizon. The injection duration is a function of formation permeability and can vary typically from 2 to 12 hours or more, depending on the radius of investigation required. Decay is typically monitored for a period equal to at least twice the injection period, although in higher permeability formations this can be less.

- **Production testing** involves the reverse process, with fluid being produced from the test interval by either reducing the initial pressure in the drill string used to locate the test tool in the hole to promote flow in response to a pressure differential between the formation and drill string (DST testing in the petroleum context), or by actively pumping fluid from the test interval. In DST testing, the pressure build-up is measured in a post-production phase when a down hole valve is closed.

Both injection and production testing can be used to assess far field permeability by applying analysis procedures developed for petroleum and groundwater testing. (Earlougher, 1977; Bourdet et al, 1989).

3. RATIONALE FOR INTEGRATION OF STRESS AND PERMEABILITY TESTING
Integration of stress and permeability testing can be driven by two different incentives:

- In situations where the need is to obtain information on stress and permeability at the same time as independent inputs to any evaluation/design process, the driving force for combining testing is the cost effectiveness offered by being able to conduct all the necessary testing with a common set of equipment, and similar testing philosophy, at the one time.

- In situations where there is an obvious relationship between rock mass permeability and stress, the driving force for combining testing may be the recognition of the need for reliable information on both parameters measured in the one testing campaign to allow the development of a geological model as a basis for understanding the relationship between permeability and stress.

Whatever the prime driving force, the advantages to be had by integrating stress and permeability testing are evident.

4. TECHNOLOGY AND TEST PROCEDURES

4.1 General
The processes involved in undertaking both hydraulic fracture stress and permeability measurements draw on a generally common philosophy. Both procedures involve the isolation of a target interval within the borehole, injection or production of fluid into/from the interval, and analysis of the pressure/flow records to evaluate the required parameters. This commonality lends itself to an integrated approach to the technology and test procedures.

4.2 Hydraulic Fracture Stress Measurement
The development of hydraulic fracture technology in Australia is well documented (Enever/Wooltorton, 1981; Enever/Walton, 1987). In the early phase of development, some key fundamentals were established:

- the need to measure stresses in the feasibility and planning stage of a project where information gained can be utilised to assist in project evaluation or contribute to the engineering design, generally dictating the requirement to operate in surface exploration holes and within drilling practices utilised by industry;

- the need for accurate initial placement and subsequent relocation of test tools within a hole at chosen target horizons to facilitate operation in situations where suitable test horizons are of limited thickness;

- the ability to conduct multi-test programmes in an efficient manner to obtain a number of data points providing a reliable estimate of the stress field in an appropriate geological context;

- the need for real time, down-hole monitoring and recording of test functions to facilitate optimum test control and data quality.

These fundamentals are still pertinent and inherent in the authors' approach to application of this technique. More recent development of the technology has concentrated on its commercial deployment and versatility, extending to the conduct of step rate tests.
Figure 1 is a schematic of the test equipment developed and employed by the authors for hydraulic fracture stress measurement. Of note are the following:

- inflatable straddle packer assembly incorporating a short stiff test zone to minimise axial forces;
- down-hole, real time pressure monitoring of both test interval and straddle packer assemblies, with signals transferred to the surface control facility via data cable;
- modified drill rods for tool placement and conduct of fluid to the test interval at high pressure without leakage;
- independent, operator controlled, low flow rate pressurisation systems dedicated to both test interval and straddle packer;
- inflatable impression packer with orientation device to establish fracture geometry and orientation.

The current test equipment has been utilised from near surface to depths approaching 1,200 m. Over 3,000 hydraulic fracture tests have been conducted to date with this equipment. Similar but simpler equipment has been used from underground openings.

For step rate testing, some additional features have been introduced (Figure 2):

- variable rate injection facility;
- recording of flow to test zone;
- down-hole shut-off valve, capable of isolating drill string from test zone, thereby minimising wellbore storage effects;
- variable test zone length.

The test procedure adopted by the authors for hydraulic fracture stress measurement is well documented (Enever, 1993). Test horizons suitable for testing (free of weaknesses) are selected by core inspection. Generally, all fracture tests are conducted before impressions are conducted.

Figure 3 is an idealised fracture pressure record which illustrates the main features of a typical hydraulic fracture test. The fracture initiation, shut-in and crack re-opening pressures can be used to calculate the magnitudes of the secondary principal stresses in the plane normal to the test hole, provided an axial fracture is formed. An impression packer is used to define the fracture geometry and orientation. The orientation of an axial fracture can be used to define the orientation of the secondary principal stress field.

For step rate tests, the procedure involves a number of incremental increases of injection flow rate at correspondingly increasing equilibrium pressure, until the flow rate increases rapidly for small pressure increase. Subsequent closure of the down-hole valve isolates the interval, allowing a closure pressure to be determined. This procedure can be repeated if required for better data definition.

Figure 1. Schematic of equipment developed for hydraulic fracture stress measurement.

Figure 2. Schematic of equipment configured for step rate testing.
Figure 4 is a typical plot of flow rate versus equilibrium pressure. Of note is the "knee" in the curve where the test pressure starts to exceed the stress normal to a fracture oriented normal to the minimum stress in the rock mass, thus opening up the fracture. This knee can generally be taken to estimate the minimum stress magnitude in proximity to the test interval, provided that the rock mass is well fractured.

In principle, the same test approach is used to conduct hydraulic jacking tests to estimate the hydraulic pressure at which a critically oriented fracture set may be jacked open.

4.3 Permeability Measurement

The application of the technology described above to the measurement of permeability was a natural process, requiring little in the way of specific adaptations, but more the development of appropriate test procedures revolving around the capabilities of the equipment. The only significant equipment enhancement has been the introduction of additional down-hole pressure monitoring capability to allow tracking of pressure changes occurring in the rod string and test hole above and below the isolated test zone during testing. This facilitates the detection of fluid short circuits that might occur during testing.

The detailed test procedures developed by the authors have been based on experience from the petroleum and groundwater industries as discussed above. The flexibility inherent in the equipment allows both injection and production tests to be conducted at will, allowing the decision as to which is the best approach in any particular case to be left to be made on site. This is a distinct advantage. Injection tests are often considered desirable because of the ability to analyse both the injection and decay phases to produce a check on the internal consistency of the data. Production tests offer an advantage in cases where the excess (over piezometric pressure) injection pressure may risk hydraulic jacking occurring, leading to an inflated estimate of permeability compared to the inherent value.

Figures 5 and 6 are typical results obtained by the authors in coal seams, reflecting different methods used for analysis.
5. EXAMPLES OF EXPERIENCE

5.1 Three Dimensional Stress Measurements and Hydraulic Jacking

The data in Figure 7 represents the results of a program of hydraulic fracture stress measurement conducted in a volcanic sequence from an underground opening. Measurements were conducted from two approximately orthogonal holes, testing intact rock horizons in each hole, to arrive at the three dimensional stress tensor by combining the secondary principal stresses determined in the two holes. Results of this type are commonly used for the detailed design of underground excavations and a range of other purposes. One specific application pursued by the authors has been the prediction of hydraulic jacking potential of a fractured rock mass, related to the need or otherwise for a steel lining to be installed in a water pressure tunnel. By overlying the three dimensional stress tensor against the measured orientation of the poles to the various sets of fracture planes existing in the rock mass on a stereographic plot, it is possible to identify the potential for hydraulic jacking, the worst case being represented by the alignment, or near alignment, of the minimum principal stress component normal to the orientation of a fracture set in the rock mass.

An alternate and/or complementary approach to the prediction of hydraulic jacking potential is to conduct a hydraulic jacking test on selected fracture planes with different orientations, intersecting one or more test holes, to directly measure the pressure at which the fracture plane is "jacked" open. By isolating fractures (one fracture per test preferably) representing each of the major fracture sets in the rock mass, a range of hydraulic jacking pressures can be determined from which the minimum jacking pressure can be selected. An example of this approach is shown in Figure 8.

The same equipment can be used for both the above testing programs.

5.2 Integrated Stress Measurements and Permeability Determinations during Site Investigations

Figures 9 and 10 represent the results of hydraulic fracture stress measurement programs conducted from deep surface holes in sedimentary sequences.

Figure 10 summarises the orientation of the horizontal stress field measured across an underground coal mining lease in the rock units overlying the coal seam destined for extraction. Information of this type is critical to the design of optimum mine layout. The use of hydraulic fracturing for this purpose has become accepted as routine by the Australian coal mining industry. Drivage directions and longwall face alignments are commonly decided with reference to the horizontal stress field orientation.

Figure 8. Typical result of hydraulic jacking test conducted on a single fracture plane

Figure 10 summarises the stress field magnitude profile with depth measured by hydraulic fracturing at the site of a planned major underground excavation. Information of this type provides a basis for the rational design of excavation layout, shape, support requirements etc. The value of this approach is now widely recognised in Australia.

The examples outlined above illustrate the use of hydraulic fracture stress measurement in mining and civil engineering applications for initial planning. In addition, in both the examples given, permeability measurements were made in parallel with the stress measurements. In both cases the injection/decay procedure outlined above was employed to produce estimates of permeability. In the mining example, the distribution (both laterally and vertically) of permeability in the target coal seam was measured as a fundamental input to planning seam water/gas handling strategies. In the civil engineering example, the matrix permeability of the rock mass was required for the design of water flow control measures associated with the function of the final facility. These examples illustrate the type of application where advantage can be taken of the synergies offered by being able to measure both stress and permeability.
5.3 The Relationship between Stress and Permeability

Apart from the cost efficiencies offered by parallel measurement of stress and permeability when information on both parameters is required for the particular application, there are situations where knowledge of both stress and permeability can help in giving a fundamental understanding of the relationship between the two. One such situation is the prediction of fluid flow rates in fractured media, where the transmissivity of the fractures is controlled by the prevailing stress field.

Figure 11 summarises the results of a program of permeability measurements (by injection/decay) and minimum stress magnitude determination (by step-rate) conducted in a sequence of coal seams intersecting a coalbed methane exploration. In this context coal can be considered as a fractured medium. Effective stress represents the measured minimum total stress less the reservoir pressure measured in the coal during permeability testing. The apparent systematic relationship between effective stress and permeability is very evident from Figure 11. In the exploration context, this leads to the notion of trying to locate regions of low stress and consequent high permeability (maximum production rates) and of basing predictions of potential productivity on the stress state.

6. CONCLUSIONS

The potential advantages offered by the integration of hydraulic fracture stress measurement and permeability testing in many circumstances is demonstrated by the experiences outlined here. The flexibility offered by the equipment developed by the authors facilitates the conduct of both types of measurement in a cost effective manner.

8. REFERENCES


