ARMA 21– 2034

The Hydraulic Fracturing Method of In-Situ Stress Testing from a Field Equipment Perspective

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ABSTRACT: The hydraulic fracturing method of rock stress testing as described in ASTM (ASTM D4645-08) and ISRM (Haimson & Cornet, 2003) is conducted to characterize in-situ stress for a variety of applications in the energy, civil, mining, and geotechnical fields. A review of downhole and surface equipment utilized to perform the hydraulic fracturing method is presented. Significant improvement in the performance of open-hole hydraulic packer systems has been achieved over the past 20 years as a result of production-style hydraulic fracturing treatments in block cave mining in Australia and Chile. In one mine alone, it is estimated that more than 250,000 treatments have been conducted. As a result, inflatable straddle packer systems that can withstand up to 90Mpa are now readily available and cost effective due to the volume of equipment manufactured for block cave mining. The pressure and flow required to perform successful tests varies widely depending on rock type, rock quality, depth and local stress regimes. A simple analysis is presented to demonstrate that a one-size-fits-all technical specification of minimum recommended pressure and flow requirements can result in unnecessary project costs.

1. INTRODUCTION

The hydraulic fracturing method of rock stress testing as described in ASTM (ASTM D4645-08) and ISRM (Haimson & Cornet, 2003) standards is conducted to characterize in-situ stress for a variety of projects in the civil, mining, and geotechnical fields. While the exact pressure and flow required to complete a successful field campaign is impossible to predict, it is critical to have a sound estimation of what is reasonably expected. Underestimating the equipment requirements can result in an unsuccessful and costly test campaign, whereas erring on the side of caution, i.e. over-specifying pressure and flow requirements, can result in unnecessary cost and effort for a given project. The purpose of this paper is to explore "right sizing" the field equipment for successful in-situ stress measurements with the intent to provide a resource for those who are specifying job requirements to contractors, and for those contractors who are tasked with carrying out the field measurements.

The ASTM standard for hydraulic fracturing stress measurement (ASTM, 2008) recommends a 70 MPa pumping capacity; however, this level of breakdown pressure is seldom seen in actual field tests. Actual breakdown pressures are generally below 20 MPa for tests shallower than 500 m, and 40 MPa for tests shallower than 1 km (Figure 1 and Doe, 2021, this volume). Breakdown pressures depend on the general magnitudes of the in situ stresses and will be greatest in regions that have stress conditions corresponding to thrust faulting conditions. Tests that are performed at sites where the stress conditions correspond to normal faulting or strike slip faulting will generally have lower breakdown pressures as will test locations at depths above the base topography. Under these conditions, pressure capacities as low as 20 MPa may be sufficient. On the other hand, variable elastic properties in rock masses with different rock types, such as shales and limestones or sandstones and dolerites may also create highly heterogeneous stresses. In summary, designing test systems for specific sites must consider the likely stress conditions based on tectonic setting and topography as well as stress variability based on the range of lithologies present.

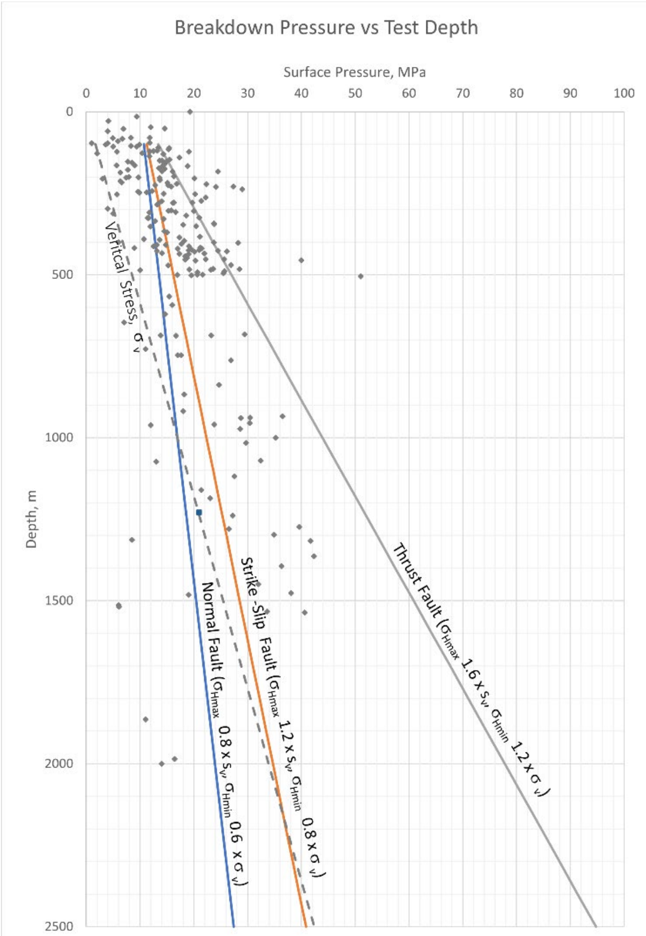

Fig. 1. Surface-measured breakdown pressure as a function of depth for three stress conditions with comparison to the sampling of published literature values (Source: Doe, 2021).

2. FIELD EQUIPMENT

The field equipment for open-hole testing generally comprises the following components:

A. Inflatable packer straddle tool to isolate the test interval,
B. Pump system to provide the pressure and flow required for testing,
C. Flow and pressure conveyance system, and
D. Data acquisition system to monitor and record test data.
E. Impression packers or borehole imaging techniques to measure fracture orientation.

Each of the above listed components is available over a range of specifications. The cost of some components is highly sensitive to the specification while others are less so. It is important to evaluate each component to identify critical aspects to consider when planning a field campaign.

2.1. Inflatable Packer Straddle Tool

The target zone for a hydraulic fracture test is isolated using an inflatable straddle packer system consisting of two inflatable packers that seal against the borehole wall, and an injection port between the packers for transmitting flow and pressure to the test zone. Straddle tools for hydraulic fracturing tests range from standard external inflate systems common for shallow testing (<500m) to complex tools with downhole controls that exist in the oil & gas service sector and are utilized in deeper settings. Critical features when evaluating packer systems include ease of running in and out of the borehole, ease of redressing the system, system compliance, pressure and temperature rating, accommodation of down-hole pressure sensors, and of course, cost.

Significant improvements in the performance and availability of open-hole hydraulic packer systems have been achieved over the past 20 years by the advent of intensive hydraulic fracturing treatments in block cave mining for rock burst mitigation and ore body preconditioning. Typically, multiple fracture treatments are conducted in each borehole with a spacing between zones of 1-2 m, with a 100 m borehole having 50+ individual fracture treatments. In one mine in Chile, it is estimated that more than 250,000 treatments have been conducted. As a result, there has been gradual improvement in the durability and user-friendliness of inflatable straddle packer systems.

Tool improvements designed to meet the demanding environment of production fracturing treatments also benefit the suitability of those tools for rock stress measurements, including increased pressure ratings, optimized test interval profiles, and decreased compressibility or compliance. Tool pressure ratings have increased to 90 MPa with little or no increase in system cost compared to systems capable of <30 MPa. Tools are now designed with flush outside diameter equal to the at-rest packer diameter through the test interval (Figure 2). This reduces the risk of the tool hanging up in the borehole and decreases the test interval volume, which in turn minimizes system compliance.

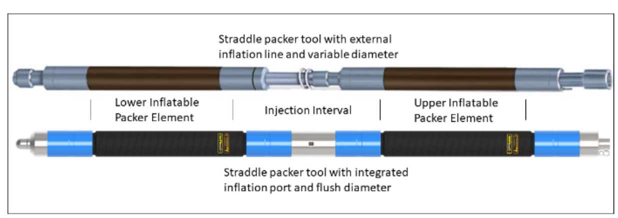

Fig. 2. Comparison of packer straddle tools with variable and flush diameters in the test interval.

Increased rigidity in the rubber packer elements because of the increased reinforcement to achieve higher pressure rating has the added benefit of decreasing the system compliance (compressibility), which in turn increases the dynamic sealing capacity of the packers. Dynamic sealing is a characteristic of liquid-inflated packers wherein the packer pressure is "boosted" by the injection pressure in the interval (Figure 3). In this case, the packer was initially inflated to 7 MPa (~1000 psi) to create a seal against a test pipe. As the differential in the injection interval was increased step-wise to 30 MPa (~4400 psi), the packer pressure increased and maintained a positive seal in the test pipe without any manipulation of the packer inflation pressure.

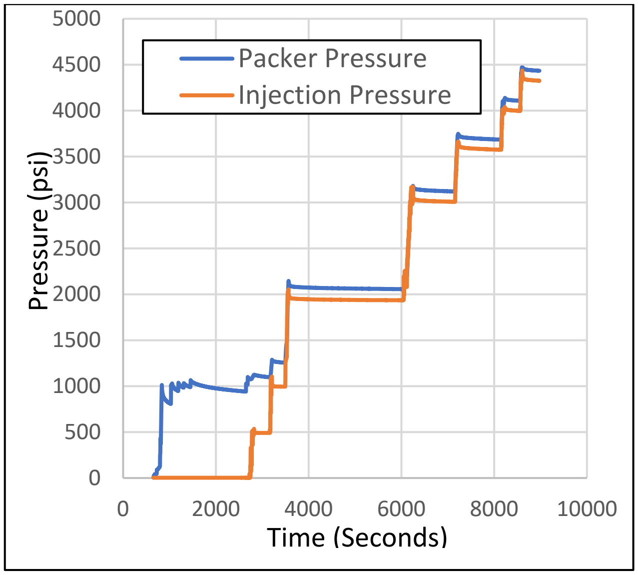

Fig. 3. Graph showing the pressure boost effect on inflatable packers.

The amount of pressure boost is highly dependent on the rigidity of the packer, and in this author's experience, ranges from approximately 1 MPa (~150 psi) for low rigidity, 3 to 4 MPa (~400 to 500 psi) for medium rigidity, and up to 14 MPa (~2000 psi) for high rigidity packers. There are three important take-aways from the packer boost observations:

1) For water or oil inflated packers, it is only necessary to inflate the packers to borehole touch-wall pressure plus moderate additional pressure to create an adequate seal for conducting hydraulic fracturing tests. An initial packer inflation pressure of 3.5 to 7 MPa (~500-1000 psi) is adequate for most hydraulic fracturing applications.
2) The more rigid the packer (generally associated with packers having higher pressure rating), the greater the pressure boost effect.
3) The more rigid the packer, the lower the compliance of the test system.

2.2. Pump System

High pressure pumps are used to generate the pressure and flow needed to conduct a hydraulic fracture test. The pressures required for the majority of tests as discussed above range from 20–30 MPa. The flow requirements of the test system depend on three things: the compressibility of the test system overall (system compliance), the permeability of the rock, and the size of the induced fractures. Typical requirements for the pumping rates in a hydraulic fracturing stress measurement (Doe, 2021) are less than 2 liters per minute (lpm) for fracture initiation and 15-20 lpm for stepped pressure tests (hydraulic jacking). Much higher rates might be required if stepped pressure tests are performed on conductive fractures rather than on borehole intervals that are initially free of fractures (Doe, 2021).

Two types of pumps commonly used for hydraulic fracturing tests are the following:

- Triplex pumps
- Pnuematic-driven liquid pumps (air-over-water)

Triplex pumps are by far the most common and can produce both high flow and high pressure. Air-over-water pumps are the most economical for producing high pressure, however they tend to have lower flow rate capabilities.

The cost of pumping equipment increases drastically with increased pressure and flow requirements. Commercial pressure washers that produce 29 MPa (4200 psi) and 15 lpm can be purchased for less than US$2000, whereas pumps capable of meeting the ASTM recommended 70 MPa and 26 lpm will cost upwards of US$40,000 and generally require custom fabrication with long lead times. Higher capacity pumps also require high HP drive sources and have a large footprint that can be a challenge to mobilize to remote sites. Hydraulic jacking of pre-existing permeable fractures is likely the only application that will require high-pressure, high-flow pumping capacity.

2.3. Flow and Pressure Conveyance

Flow and pressure are conveyed from the surface pump unit to the test zone via either the drill pipe that is used to deliver and support the packer system, or a separate dedicated high-pressure tubing. Although the conveyance system is the least technical component of hydraulic fracturing testing equipment, it can be the most problematic, especially when, for instance, a drilling contractor who may not be knowledgeable in hydraulic fracturing is required to supply the conveyance system. Meeting a 70 MPa and 26 lpm specification can be quite difficult for the following reasons: a) drill pipe or rods available are rarely rated for 70 MPa and are usually not leak tight, and b) dedicated high-pressure hose or stainless-steel tubing that satisfy 70 MPa pressure requirements is generally nominal ¼-inch or 3/8-inch tubing with small flow through area resulting in extreme friction loss at specified flow rates.

In some cases, drill pipe can be modified to include o-ring seals which eliminate the leakage, but do not overcome the pressure rating hurdle. Consultants who own a complete suite of equipment have had high-pressure conveyance pipe custom made to their specifications.

Dual-wall rods that combine packer inflation and test-interval injection in an integrated package are an option that eliminates running an external inflation line and streamlines installation. The system has o-ring seals on all connections and is rated up to 70 MPa. While the dual-wall rod system is targeted for the block cave mining market, it is applicable for rock stress testing as well. The cost is higher than single wall options but provides a number of technical and operational advantages.

2.4. Pressure and Flow Monitoring

Recording accurate pressure and flow data is a vital part of hydraulic fracture testing. Data sampling rates of 10 Hz or faster are recommended. Numerous data acquisition systems for digitizing and recording data adequate for testing purposes are readily available and will not be discussed in detail here.

Pressure monitoring can be done at surface, down hole, or both. Measuring pressure at the surface using standard industrial sensors is simple but requires additional analysis to account for static formation pressures and friction loss in the conveyance system. Measuring downhole pressure eliminates the need to account for friction loss between the test interval and the injection source; these can be real time sensors that transmit the pressure signal to surface via a data cable, or data logging transducers (known as "memory gauges" in the energy industry) that are downloaded after retrieval of the packer system. Down hole pressure measurement can be critical when using small-diameter tubing or hose for fluid conveyance from the surface.

Real-time downhole pressure signals are the best solution for observing true downhole conditions during a test and doing on-the-fly test interpretation and making any necessary adjustments in the procedures. However, they add to the complexity of running tools in and out of the borehole because care must be taken not to damage the data cable.

Datalogging transducers in the test interval combined with pressure monitoring at the surface is a viable solution when running data cables down hole is not desired. The surface measurements provide a real-time indication of down hole conditions for quality control purposes and troubleshooting during testing. Once recovered, the data logging transducers provide accurate test interval conditions for conducting final test analysis. Standard data logging transducers from the hydrogeologic monitoring industry are limited to about 7 MPa pressure rating and are not suitable for hydraulic fracturing. However, a number of suppliers in the energy sector provide high pressure "memory gauges" on a rental basis, which can be advantageous for individual projects. Packer systems can have integrated gauge carriers or threaded ports for securely accommodating the sensors.

Flow measurement can be a particular challenge at high pressure. Meters using internal measurement methods, such as turbines and gears generally do not meet the pressure ratings require for hydraulic fracturing, and if they do, then tend to be very expensive and bulky. Flow meters with no internal workings, such as ultrasonic and mass flow meters (Coriolis) are viable choices for measuring flow on the high-pressure side of the injection system. An option for flow measurement before the injection pump is to monitor injection volume using a digital scale under the water source and converting change in mass to a flow rate. This method is well suited for low flow rates that can be difficult to capture using flow-through measuring devices. Higher flow rates can be measured using a digital pallet scale and suitable water vessel.

2.5. Fracture Delineation and Orientation

The final step in hydraulic fracture field measurement, determining the fracture delineation and orientation, is achieved using either an oriented impression packer, or borehole imaging. The advantages and disadvantages of each method are described in Haimson & Cornet, 2003, and ASTM D4645-08. This paper focuses on factors that may drive cost for field conditions such as formation magnetism and borehole geometry.

The cost variability of borehole imaging depends largely on the availability of equipment and whether it has been mobilized to site for other purposes. The cost for the impression packer method can vary significantly depending on the type of orientation device that can be utilized in each situation.

The following types of orientation devices can be used:

1) <u>Magnetic</u> compasses are the least expensive, most available and can be deployed in any borehole geometry. However, they cannot be used in magnetic formations.
2) <u>Gyroscopic</u> compasses are the costliest option, but can be used in magnetic formations. There are two types of gyroscopic tools on the market; N-seeking and reference. N-seeking gyros will work in all hole geometries, whereas reference gyros, which are less costly, will work in all but vertical orientation and require the additional step of referencing the device on surface.

3) Gravity devices designed for core orientation in diamond drilling can be employed for fracture orientation in non-vertical boreholes. These devices are often on site for drilling purposes and therefore very cost effective and can be adapted to an impression packer as shown in Figure 4.

Fig. 4. Left photo showing impression packer (blue section above) combined with core orientation device (bottom) prior to deployment, and right photo showing the transfer of fracture traces to film post-deployment.

3. CONCLUSIONS

The various components of a suite of hydraulic fracturing equipment have differing levels of cost and availability sensitivities to individual project requirements. "Right sizing" equipment for conducting in situ rock stress measurements using hydraulic fracturing is one of the keys to successful projects. Doing so requires input from knowledgeable professionals at every step of the process including scoping the project, specifying equipment, and executing the field testing.

4. ACKNOWLEDGEMENTS

The author thanks Dr. Tom Doe for his valuable input on the documented breakdown pressures and flow rates from field testing, as well as Francis Ford and Kyle Markham for providing data regarding packer boost dynamics.

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