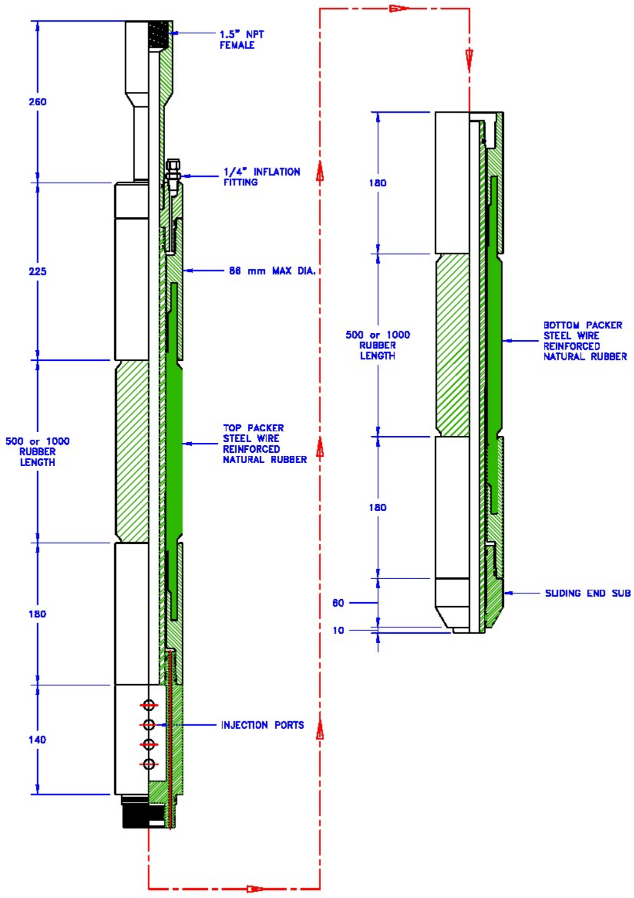

Equipment Description

1. Hydraulic stimulation is a long established system for improving the yield of water and oil wells by creating substantial fractures at pre-determined locations in the ground. A miniature version of the same technique can be used to identify the insitu stress state of rock and some soils. The procedure is to isolate a portion of a borehole, then hydraulically pressurise the isolated section until tensile failure occurs at the cavity wall. In ideal circumstances information gathered directly from the pressure record allows the minor and major principal horizontal stresses to be determined, together with the tensile strength of the rock.
2. The downhole tool used by CI consists of a straddle packer and a pair of pressure lines that allow separate pressurisation of the packer sleeves and the isolated section. This arrangement is ideal for relatively shallow tests. The packer sleeves are pressurised with compressed air. Pressure transducers and flow sensors at the surface allow the pressure/time and flow/time data to be recorded electronically, and these data are collected automatically using a proprietary data logging system.
3. The system is dimensioned to operate in an 'H' size borehole and the isolated section acts on a 0.5m length of borehole. This is the shortest length that can realistically be managed and maximises the possibility of being able to test an unbroken section of material. In practice, by the time the packers are inflated to the

dimensions of the larger cavity, the exposed length is about 0.65 metres. Further details of the equipment used are available upon request.

4. A full interpretation requires that the orientation of the induced fracture be known. In a vertical borehole in uniform rock where the horizontal stress exceeds the overburden stress it is expected that a new fracture will also be near vertical. It will then indicate the orientation of the major principal stress in a plane normal to the axis of the borehole.
5. There are two options for fracture identification - The tested area can be examined using downhole logging tools such as an acoustic televiewer to take pre and post-test images for later interpretation and comparison. Alternatives, an impression packer with a compass could be deployed to make an image of the cavity surface post-test, although CI do not currently operate impression packers.

<u>Test Procedure</u>

1. Once the test pocket has been drilled, the core is inspected and an acoustic televiewer is used to produce a pre-test image of the pocket walls.
2. Prior to lowering the probe into position, it is assembled on the surface with both hoses attached and a restraining metal cylinder placed over both packers.
3. The packers are inflated pneumatically. Water at pressure is injected into the central testing section. The water pressure is allowed to climb whilst the system is checked for leaks. Once the pressure exceeded the packer pressure, water flows past the packers. The packer pressure is increased to stop the flow. This completes the checks - water and packer pressure are vented.
4. The probe is connected to the first drill rod. A final check is made of measurements, the rods are counted and the last rod has a ring of tape placed indicating when the probe will be at the correct depth.
5. The probe is lowered down the borehole with the umbilical lines taped to the drill string at 6 metre intervals.
6. Once at depth, the rig clamps are used to hold the drill string and probe in place.
7. An estimate is made of the overburden stress. Twice this amount plus 1MPa is applied to the packers.
8. Some water is injected at a steady rate of flow into the probe. A hand pump can be used if the required flows are low. If higher rates of flow are necessary then an air driven water pump is used to raise the injection pressure.
9. **Permeability check** - Once the injection pressure is 500kPa or thereabouts (for shallow depths) the injected pressure is locked off and the output monitored for 5 minutes. A small amount of pressure decrease is expected due to the natural permeability of the formation, but the pressure should remain stable. This is a check that the system and pocket are holding pressure, and there is no significant loss through open fractures. If this check is failed, then the test would be aborted at this stage.
10. **Breakdown cycle** – If the above check is satisfied, the water pressure is raised using a constant rate of flow until breakdown occurs. Once this happens the pressure is locked off and the decay through the newly created or newly extended fracture monitored until the water pressure reaches a constant value.

11. **Reopening cycle(s)** – The section is pressurised again at a constant flow until the newly created fracture re-opens. The pressure is locked off and the decay monitored. This repeated as many times as required until a consistent response is seen.
12. In between re-opening cycles it is helpful to completely vent the water pressure and then re-apply it when there is uncertainty about the re-opening pressure.
13. Once the respective pressures have been recorded, the system is deflated before the packers are moved and the test repeated within the same pocket. It is common to undertake two or three pressurisation episodes in the same pocket at different levels in order to qualify the results.
14. Following the test sequence, the probe is removed from the borehole and a post-test televiewer image is taken of the same test pocket.

1.3 Analysis of the test

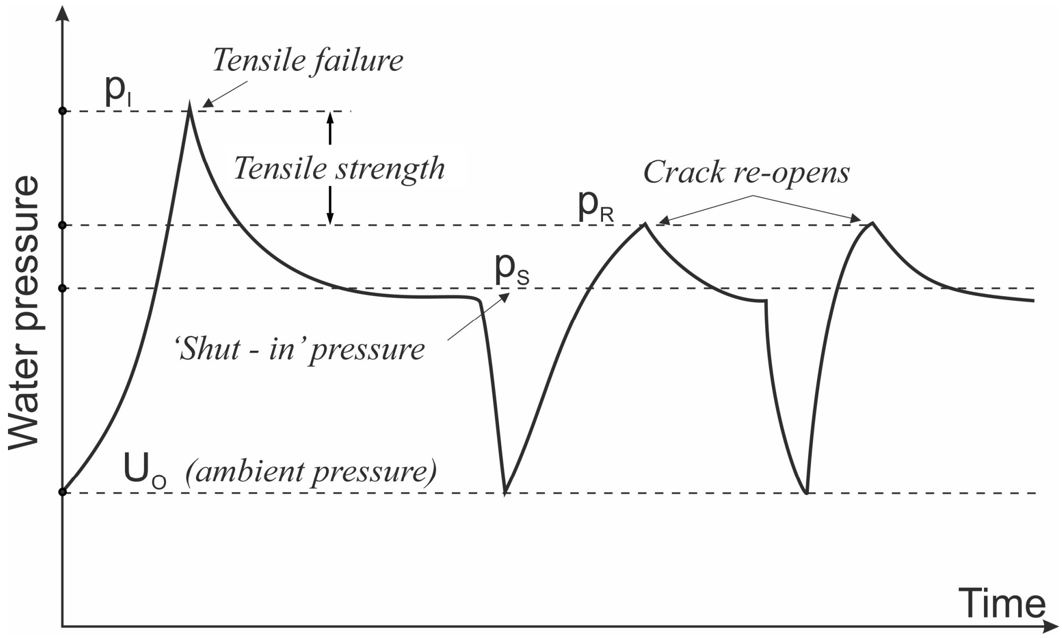

Fig 1.1 Sketch of the hydraulic stimulation test – Hubbert & Willis (1957) interpretation

Conventional Analysis Method for Vertical Fractures

1. HS testing for lateral stress parameters ideally is undertaken in rock that is free of fractures.
2. The conventional analysis of a hydraulic stimulation test demands that new vertical or near vertical fractures are created, which is only possible if the vertical stress exceeds the horizontal stress at the test horizon. It is therefore not usually an appropriate method for relatively shallow testing.
3. If the induced fractures are vertical or nearly so, then the simple procedure of Hubbert and Willis (1957) can be used. It is derived from the well-known solution for stress distribution around a circular opening and assumes that the ground is a

homogeneous and isotropic elastic continuous medium. The rate of loading is assumed to be fast enough to prevent gradients of pore pressure in the formation.

4. The analysis itself starts by identifying three key stress levels in the pressure versus time record (fig 1.1). The first is the break-down stress required to crack the rock. The second is the pressure at which the new crack closes. The third is the pressure required to re-open the fracture. The second stress is the most critical to establish, and multiple loadings are carried out until a consistent response is seen. Having completed the stress analysis, the orientation of the horizontal principal stresses is calculated from the direction of the induced fracture.

Considerations for Analysing Non-vertical or Existing Fractures

1. If the tests are shallow and/or the vertical stress does not exceed the horizontal stress at the test horizon, then non-vertical or even existing fractures are more likely to be opened up during the test.
2. In this situation it is possible to apply the published methods of Cornet and Valette (1984) or Kuriyagawa et al (1989) which are usually referred to as the HTPF method (for 'hydraulic tests on pre-existing fractures'). It requires finding 4 stress constants and two directional constants by iterative means, from which the lateral stresses can be deduced. The full equations are available upon request.
3. The essence of the Cornet & Valette argument is that all stresses increase linearly with depth and the Authors suggest a means by which this assumption can be tested prior to complex analysis.
4. Tests of this kind require considerably more interpretation and iteration, and the usefulness of the results cannot be guaranteed.
5. For this assumption the general solution is:

$$P_R = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - u_0 \quad \text{... [a]}$$

$$P_S = \frac{1}{2}(\sigma_H + \sigma_h) - \frac{1}{2}(\sigma_H - \sigma_h)\cos 2\theta \quad \text{... [b]}$$

where P_R is the fracture re-open pressure
P_S is the fracture closure pressure
u_0 is the pore water pressure
θ is the joint azimuth with respect to σ_H
σ_H is the major principal stress
σ_h is the minor principal stress

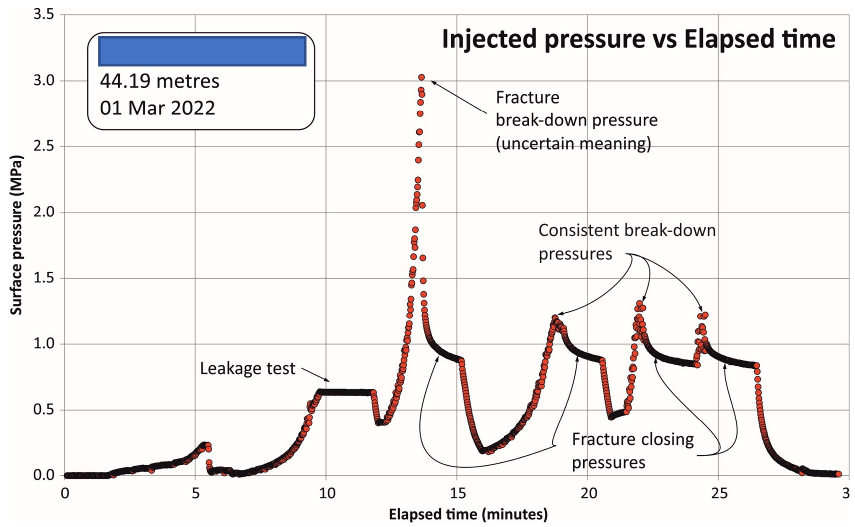

Figure 1.2 Example of test in fractured material

6. P_R is readily identified but the meaning is ambiguous. We largely ignore the break-down reading from the first cycle in favour of the re-opening stress from later cycles where the response is more consistent. P_S is the more easily applied data but obtaining it requires a little judgement. Our approach has been to take P_S from the first cycle indicating a consistent response. An example of the interpretation of the shut-in pressure for one test is given below in fig 1.3. The test itself is shown in fig 1.2 above. In the ideal case of a vertical fracture P_S gives σ_h directly, but even without knowledge of the dip of the fracture it is reasonable to assume that if $P_S > \sigma_v$ then so will be the lateral stresses.

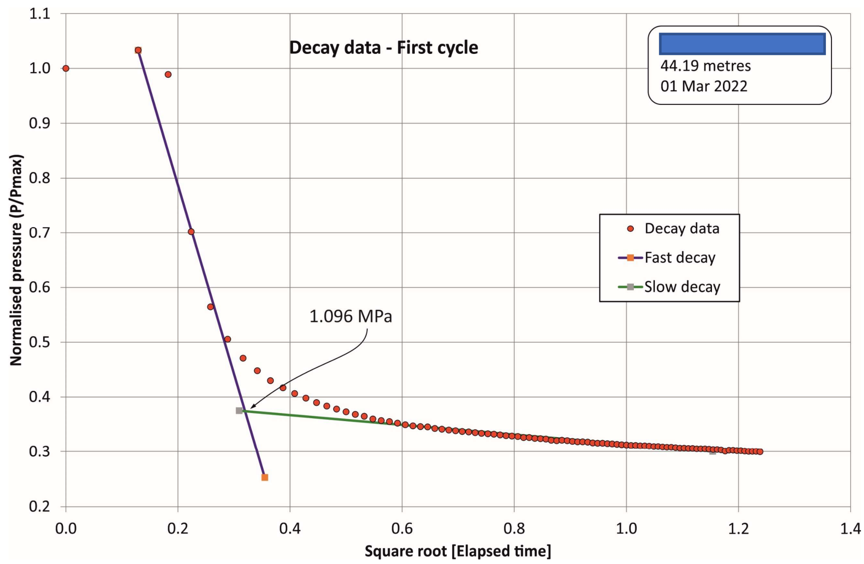

Figure 1.3 Example of shut-in pressure derivation

7. Note that the shut-in stresses are normalised by the maximum pressure (in effect P_R) at the start of the fracture closure process. The horizontal axis is square root elapsed time, giving greater emphasis to the focal point of the closure response.

8. Application of the two equations [a] and [b] is done iteratively. The most likely fracture and its inclination are identified from the televiewer data. A guess is made of the minor lateral stress σ_h and the ratio σ_H/σ_h. The guess of σ_h is modified until the value of P_S obtained from [b] agrees with the measured value for P_S derived from plots such as fig 1.3. The process also gives a derived P_R that can be compared with the measured P_R. Altering the lateral stress ratio allows this to be modified but in practice the calculated value is always slightly greater than the measured value. This seems reasonable, in view of the flow rate dependency of the re-opening stress, whereas the other way around would not.
9. Orientation : The bearing of the major stress to magnetic north is given by recognising that θ in [a] and [b] is the subtraction of the fracture strike with respect to north and the orientation of the major lateral stress with respect to north. The fracture strike is given by the televiewer log, the second value is selected for best fit to all the data in the borehole.