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Two New Methods for Defining Shut-In Pressure in Hydraulic Fracturing Tests

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Abstract

Hydraulic fracturing is one of the most common methods to determine in situ rock stress. The interpretation of the shut-in pressure to determine the minor principal stress is an important element of this method, and many different methods to interpret shut-in pressure have been studied and developed throughout the years. Each method has its advantages and disadvantages. With more than 50 years of research and development within the rock stress measurement field, especially in HF, SINTEF has established two practical ways of defining shut-in pressure. These methods are independent and termed *zero flow* and *water hammer*. The *zero flow* method has been used by SINTEF in more than 130 projects over the last 30 years. The methods clearly differ from the other methods as they are based on singular events in the development of pressure/flow versus time which enables us to read the shut-in pressure directly during testing. In this paper, a comparison is made between different methods for interpretation of shut-in pressure, including 12 existing methods and the 2 SINTEF methods. Comprehensive laboratory tests were performed, and a field test was selected from SINTEF's database for demonstration and comparison of the methods. The SINTEF methods have been developed mainly for use in hard rock environment where the rock is a jointed aquifer and with low permeability. The application of the two methods has traditionally been hydroelectric power development, different types of tunnel, and cavern projects, and also in mineral mining. The methods have not been used in deep petroleum applications such as oil wells or offshore in porous rock types.

Highlights

- There are 12 established methods for shut-in pressure estimation in hydraulic fracturing. All methods have certain advantages and disadvantages.
- SINTEF has developed two methods namely zero flow and water hammer.
- The SINTEF methods are documented through laboratory and in-situ tests.
- A comparison of the two SINTEF methods with the existing methods has been done.

1 Introduction

Hydraulic fracturing (HF) is a commonly used borehole field test method designed to assess the state of in situ stress, especially at great depth, where the test locations are only accessible by drill holes, given that the test hole is oriented along the major principal stress component. HF test in a drill hole was described thoroughly in Amadei and Stephansson (1997), and it can be summarised as follows:

- Pump water into a non-fractured test section in a drill hole, the test section is isolated by inflatable double packers.
- Increase water pressure until a new fracture is created in the test section.
- Continue pumping to extend the fracture into the rock formation to a depth of at least 2–3 times the borehole diameter, before the water supply is shut-in.

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Fig. 1 Idealised pressure time history recorded in a HF test (Amadei and Stephansson 1997)
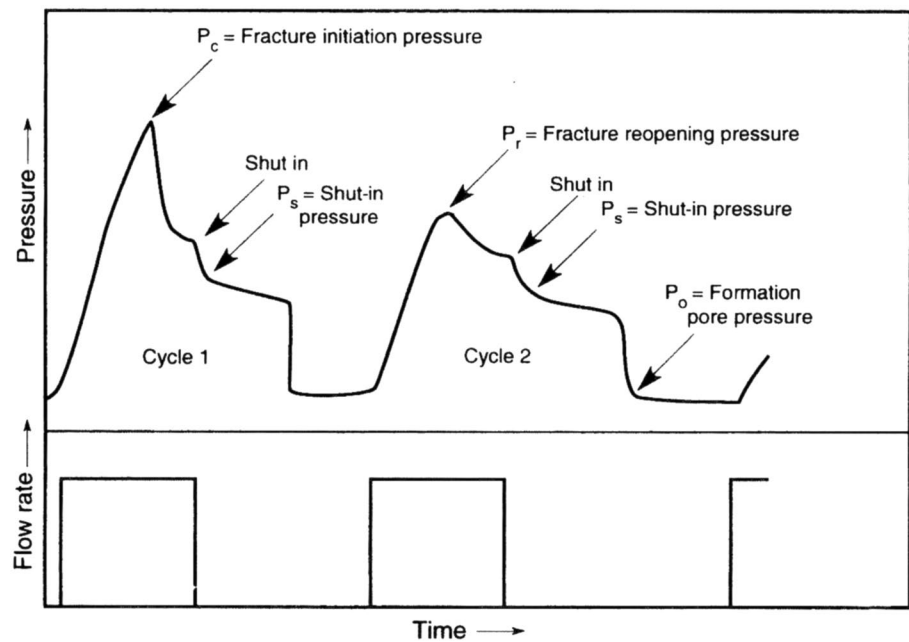
- Repressurize the test section for at least two additional cycles to measure re-opening pressure and repeat the measurements of the shut-in pressure.
- Record the entire process by precise logging of time, pressure and water flow rate.
- From the continuous log of pressure versus time, the breakdown pressure, shut-in pressure and re-opening pressure can be estimated—as shown in Fig. 1.
- Orientation of the fracture can be obtained using an impression packer.

The typical concept of a HF test is shown in Fig. 1.

From the results of a HF test, the minor principal stress component can be estimated by interpretation of the shut-in pressure. The shut-in pressure is complicated to estimate in a HF test and consequently many methods have been developed over the years. The existing methods are mostly graphic based with the construction of tangential or best-fit line(s). Each of the existing methods may be best suited for certain specific conditions and less suited, or even unsuitable for other conditions, as shown in Guo et al. (1993). Some of the methods seem to be subjective, that is being dependent on the person interpreting HF data. Thus, it appears that there is a need for a method that is more objective or generic, and more efficient.

This paper reviews 12 available methods used to determine shut-in pressure. Further, the paper presents two methods developed by SINTEF. The SINTEF methods do not use additional tangential or best-fit line(s), but the shut-in pressure can be determined directly during the test in situ. Demonstration and comparison of the SINTEF methods with well-known methods have been carried out through comprehensive laboratory HF tests and selected in situ tests.

One note to the above figure. A more suited definition of P_c in Fig. 1 may be "breakdown pressure", as fracture initiation occurs at a lower pressure before the breakdown pressure.

2 Interpretation of Shut-In Pressure—Definitions and Methods

According to ASTM suggested method (2004), the shut-in pressure in a HF test is defined as following: "*shut-in pressure, or ISIP (instantaneous shut-in pressure)—the pressure reached when the induced hydrofracture closes back after pumping is stopped*". In the ISRM's suggested method (2003), the shut-in pressure is defined as following: "*upon reaching breakdown pressure (or fracture opening), stop pumping but do not vent. Interval pressure will decay, first at a fast pace while the HF is still open and growing, and then at a much slower pace, after the fracture has closed. The pressure at which the fracture closes is termed shut-in pressure*". In the methods presented by other authors, the instantaneous shut-in pressure (ISIP) is interpreted as the minimum downhole injection pressure required to hold the induced crack open (Hayashi and Sakurai 1989). It seems that ASTM considers shut-in pressure and ISIP being the same, whilst the ISRM considers shut-in pressure as the pressure when "the hydrofacture closes"—without further details.

In our opinion, definitions from both ASTM and ISRM are still loose. In fact, the facture closure should be

considered as a process with certain time duration from when the hydrofracture starts to close until it is closed. The time elapse for the two sides of the hydrofracture to move towards each other from a fully open position to a completely closed position could be seconds or less than a second depending on rock behaviour. The amount of time taken for the fracture closure process may vary depending on the degree of opening, the stress acting perpendicular to the fracture, and the rock behaviour (for a hard rock, it may take few seconds as shown in later section with in situ HF tests). No matter the duration of the closure process, the pressures at the beginning and at the end of the process can be different. The ISIP seems to be defined as the pressure at the starting point of the fracture closure process, and closure pressure seems to be the pressure at the end of the process. Neither ASTM nor ISRM are clearly distinguishing between these two pressures, consequently when evaluating shut-in pressure, different methods may result in different pressures. ISRM (2003) mentions upper bound and lower bound pressures derived by different methods. Results from the different methods may correspond to pressure at different points in time during the fracture closure process.

In addition to the time duration of the fracture closure process, other characteristics of the process must be noted, which are (a) the closing speed during closure process may not be constant, and (b) the hydrofracture may not be completely tight at the end of the process. For example, a very small rock fragment loosened during fracturing or rock dilation/expansion after fractured may prevent the 100% tightness of the hydrofracture.

In this paper, the term "shut-in pressure" is used to cover the whole range of pressures from ISIP to closure pressure. When mentioning ISIP or closure pressure specifically, it will be clearly stated.

As shown in Fig. 1, the shut-in pressure is not occurring at the exact time of pump shut-off, but slightly after. This is due to the following: when the pump is shut-off, the flow from the pump to the test section is zero, but the fluid (water) is still flowing from the test section to the rock formation through the fracture. As a result, the fluid pressure in the test section decreases over a certain time span; that is, it is not an instant reaction. When the fluid pressure reaches the stress normal to the fracture (the minor principal stress if the drill hole is oriented correctly), the fracture stop opening, and it start to close when the pressure continues to reduce. However, the fluid from the test section is still moving due to permeation into the rock through the drill hole wall (Haimson 1993). The flow will finally stop when the fluid pressure at the test section is equal to the rock pore pressure, P_0.

Estimation of the shut-in pressure is not straight forward, and it needs a defined approach for interpretation. Guo et al. (1993), Amadei and Stephansson (1997) and Li (1999) reviewed the methods currently available for interpretation shut-in pressure. The methods are summarised in Table 1 and described as follows:

1. Tangential divergence method or inflection method: The inflection point method suggested by Gronseth and Kry (1981) and Gronseth (1982) is a simple graphical technique. The construction consists of drawing a tangent line to the pressure–time record immediately after shut-in. The pressure at which the pressure–time record departs from the tangent line is defined as the shut-in pressure. This method was suggested to interpret low-rate HF data (< 50 l/min).

2. P_w versus $\log((t + Dt)/t)$ method: McLennan and Roegiers (1981) suggested that the inflection point (a slope change) in the plot of P_w versus $\log((t + Dt)/Dt)$ represents the shut-in pressure, where P_w is the bottom hole pressure, t is the time of injection, and Dt is the time since shut-in.

3. P_w versus $\log(t)$ method: Doe and Hustrulid (1981) obtained the shut-in pressure using the plot of P_w versus $\log Dt$ for the period immediately following the

Table 1 Summary of available methods for estimation of shut-in pressure

No.	Name of the methods	References
1.	Tangential divergence or inflection method	Gronseth and Kry (1981) and Gronseth (1982)
2.	P_w versus $\log((t + Dt)/t)$ method	McLennan and Roegiers (1981)
3.	P_w versus $\log(t)$ method	Doe and Hustrulid (1981)
4.	$\log(P_w - P_a)$ versus t method (Muskat method)	Muskat (1937), Aamodt and Kuriyagawa (1981)
5.	$\log(P_w)$ versus $\log(t)$ method	Zoback and Haimson (1982)
6.	dP_w/dt versus P_w method	Tunbridge (1989)
7.	P_w versus $\ddot{O}Dt$ method	Sookprasong (1986)
8.	Maximum curvature method	Hayashi and Sakurai (1989)
9.	Tangent intersection method	Enever and Chopra (1986)
10.	P–Q method	USGS (1987)
11.	Exponential pressure decay method	Lee and Haimson (1989)
12.	Bilinear pressure decay rate method	Tunbridge (1989)

first breakdown, where Dt is the time since shut-in. The shut-in pressure corresponds to a break in the slope of the plot. The method was recommended for interpreting HF under slow pumping cycles.

4. Log(P_w–P_a) versus t method (Muskat method): Aamodt and Kuriyagawa ([1981]) thought that the pressure after shut-in approaches some value asymptotically. A trial value for this asymptotic pressure, P_a is chosen and the logarithm of the pressure P_w minus P_a is plotted against time. P_a is varied until the curve, after an initial transient, is best fitted by a straight line. The straight line is extrapolated back to the time of shut-in, giving a pressure. Then this pressure plus P_a is taken as the shut-in pressure.

5. Log(P_w) versus log(t) method: As stated by Zoback and Haimson ([1982]), Haimson recommended selecting the shut-in pressure from the plot of log(P_w) versus log(t), where P_w is the bottom hole pressure and t is the time since pumping. The pressure versus time curve in this plot is bilinear. The shut-in pressure is the intersection of the bilinear lines.

6. dP_w/dt versus P_w method: Tunbridge ([1989]) assumed that the shut-in curve is bilinear in the plot of dP_w/dt vs P_w, where P_w is the bottom hole pressure. The intersection of the two lines corresponds to the shut-in pressure.

7. P_w versus $\ddot{O}Dt$ method: Linear flow though fracture will lead to a linear relation between the pressure and $\ddot{O}Dt$. Therefore, when the plot of P_w versus $\ddot{O}Dt$ departs from a straight line, the fracture closes. The corresponding bottom hole pressure is the fracture closure pressure of the shut-in pressure (Sookprasong [1986]).

8. Maximum curvature method: The bottom hole pressure at the point of maximum curvature in the shut-in curve is also recommended as the shut-in pressure (Hayashi and Sakurai [1989]).

9. Tangent intersection method: This method was first used (without detailed text description) by Enever and Chopra [1986] when interpreting data of hydraulic fracture carried out at Berrigan and Lancefield, Australia. In this method, the pressure versus time graph was used. Two lines were plotted tangent to first part (sub-vertical) and second part (sub-horizontal) of the graph. The shut-in pressure was interpreted as an intersection point of the two tangential lines.

10. P–Q method: On cycles subsequent to the breakdown cycle, the pumping pressure at a constant flow rate usually stabilises. These pumping pressures are most stable when the fracture is barely open. By plotting the various flow rates against the stable pumping pressures, the ISIP can be determined. When the fracture is closed, or nearly so, plotted points fit a steep straight line curve.

When the fracture is open, the line has a shallower slope. This shallower curve is extrapolated back to the abscissa and the point of intersection is taken to be the shut-in pressure. This method works best when all the data are taken from a single cycle. This is because the fracture's behaviour may change as it is extended away from the well bore (USGS [1987]).

11. Exponential pressure decay method (Lee and Haimson [1989]): Pressure at the test section of the drill hole decays after the pump is shut-off. To some point, the hydrofracture closes completely and flow is purely through drill hole wall. It is assumed that, after this point, the pressure–time curve follows an exponential relation.

12. Bilinear pressure decay rate method (Tunbridge [1989]): Assuming a bilinear relation between the pressure and flow rate to the hydrofracture, which is often observed, a similar relation between the pressure and pressure decay rate would also hold. The intersection point of the two linear segments of the dP/dt—P curve is defined as the 'shut-in pressure point'.

To review and compare some methods in estimating shut-in pressure, Guo et al. ([1993]) conducted hydraulic fracture tests at a laboratory scale on gypstone blocks of $305 \times 305 \times 305$ mm and $610 \times 584 \times 305$ mm. True triaxial stress conditions were applied on the specimens before carrying out the HF tests. Obtained pressure curves versus time from the test were used for the estimation of shut-in pressure and compared with the applied minor principal stress. The shut-in pressures were estimated based on eight methods, and the results were compared with the minor principal stress. After comparison, Guo et al. concluded:

- The results show that the P_w versus log((t + Dt)/Dt) method (method no.2 in Table [1]), the P_w versus log(Dt) method (method no.3) obtain the shut-in pressure close to the applied minor principal stress if the first injection cycle is used. The log(P_w–P_a) versus Dt method (method no.4) obtains the shut-in pressure close to the applied minor principal stress if the subsequent injection cycles are used.

- The log P_w versus log t method (method no. 5), the dP_w/dt versus P_w method (method no. 6), the P_w versus $\ddot{O}Dt$ method (method no. 7) and the maximum curvature method (method no. 8) can sometimes obtain a shut-in pressure close to the applied minor principal stress. However, the results are unstable. For some tests, the results are meaningless.

- The inflection point method is subjective because of non-linear shut-in curves immediately after shut-in.

It is necessary to emphasise that this paper is limited to discuss methods that have been commonly used within the hydropower industry and also for the tunnelling industry. These methods have been applied widely for hydropower development, and the results obtained have many times been verified with different measurement methods (for example, overcoring method). Thus, the methods earn high confidence. Recent methods developed in oil industry, which have been presented in McClure (2022), are not included in this paper as they are not commonly used in the hydropower industry. The methods with "G-function" (Nolte, 1979 and 1988) and the derivative of pressure versus G-time (Barree et al. 2009 and McClure et al. 2014, 2016, McClure 2017, McClure et al. 2019, and 2021) would be interesting to test for HF measurements in hydropower industry. However, the use of the methods would require further understanding of similarities and differences between HF test in oil industry with great depth, and in very different geological circumstances, versus HF in hydropower, including test procedure and equipment. This topic can be presented in a separate paper.

3 SINTEF Methods in Defining Shut-In Pressure

With more than 50 years of research and development within the rock stress measurement in field, especially in HF, SINTEF has established two practical ways of defining shut-in pressure. These methods are independent and termed *zero flow* and *water hammer*. The *zero flow* method has been used by SINTEF in over 130 projects over the last 30 years. The methods clearly differ from the other methods presented in Table 1, as they are based on events in the pressure/flow time history, making it easy to read the shut-in pressure directly during testing. The *water hammer* method is the most recent method (since 2016) and have been applied in parallel with the *zero flow* method.

It is necessary to state that the two SINTEF methods have been developed in mainly hard rock, with low permeability. The SINTEF methods have been applied in dedicated drill holes being drilled from the surface for pre-construction testing and from inside tunnel during excavation stage. The length of drill holes drilled from the surface could be as long as 350 m, whilst being drilled inside a tunnel that are normally 30 m (reaching outside tunnel stress influenced zone) with a diameter of 64 mm. The methods have also been used in hard rock for other applications, such as tunnel and cavern projects, and mining. The methods have not been used in deep petroleum such as oil wells or offshore.

3.1 Zero Flow Method

The *zero flow* method has a long history in SINTEF, used for more than 30 years in over 130 projects. Most of the projects were related to unlined pressure tunnels for hydropower development, where the minimal principal stress is critical to counteract the hydrostatic water pressure in the unlined tunnels. None of the projects where SINTEF performed HF tests has experienced rock fracturing due to underestimation of the minimal principal stress. In some cases, our test results lead to re-design of the project to ensure locations with sufficient confinement, i.e. the minimum stress component is greater than the hydrostatic water pressure. This in itself is a confirmation that the concept of testing and interpreting the results works.

To better understand the *zero flow* method, a typical test record is presented in Fig. 2. As can be seen from the figure, shut-in induces a rapid reduction of the water flow in the system, resulting in a close to vertical drop of the flow rate, followed by a stabilising of the flow rate. Towards the end of this period, a very small amount of flow is still recorded in the system by the flowmeter. Even though the amount of flow is very small, it is prolonging for a certain duration, making the flow–time graph curving and flattening within this period. Towards the end of the flattening, there is a sudden drop of flow to near zero. SINTEF reads the corresponding pressure at this point of time and considers this as the shut-in pressure. As mentioned in Chapter 2, by considering the fracture closure as a process rather than an instant event, the time at the *zero flow* is towards the end of the closure process. Thus, the pressure estimated by *zero flow* method is close to closure pressure.

3.2 Water Hammer Method

SINTEF has analysed thousands of individual HF measurements from our own HF testing. It is realised that during the period between shut-in and the described *zero flow*, there is always a fluctuation in the graph of pressure versus time. This effect can only be seen in the graph with high data sampling frequency (around 50 Hz). Analyses of this event indicate that this is caused by a *water hammer* effect in the system. Pressure surge or water hammer, as it is known, is the formation of a pressure wave as a result of sudden change in liquid velocity in a piping system. The water hammer phenomenon is usually explained by considering ideal reservoir pipe-valve system in which a steady flow with velocity V_0 is stopped by an instantaneous valve closure. In other words, it occurs when the fluid flow starts or stops quickly or is forced to make a rapid change in direction; for example, quick closing the valves or shutting off a pump can create a water hammer effect (Choon 2012).

The second criterion for defining shut-in pressure is, thus, based on the observation of the *water hammer* effect. It is well known that the pressure fluctuates around a base pressure during the water hammer effect (example of the base pressure line will be demonstrated in the chapter with in situ tests and discussion chapter). It is observed that the line showing base pressure versus time is not horizontal but slightly declined as the pressure in the test section is reduced with time. Thus, defining shut-in pressure is a complicated procedure. At SINTEF, the following considerations are taken into account when defining the shut-in pressure using the water hammer method:

- Theoretically, the shut-in pressure should be defined along the base pressure line. However, it requires a complicated mathematical procedure to estimate the base pressure line from the logged pressure. Therefore, SINTEF suggests a more practical solution, as described below.
- The aim for SINTEF is to obtain the shut-in pressure directly in the logged data without constructing additional graphic interpretation. This simplification allows the obtained shut-in pressure to be defined at the site, during the in situ HF test without negotiating the quality of the identification of the shut-in pressure.
- From the argument, shut-in pressure can be defined directly from the logged data by two practical approaches as described below:

1. The shut-in pressure is considered as equal to the average value of the first and second peak of the pressure fluctuation.
2. Filter data to reduce the magnitude of pressure fluctuation to an acceptable level. The shut-in pressure is con-

sidered to be equal to the second peak of the filtered data. A computation channel on the data logger is used to filter the data simultaneously as the test is conducted.

From a practical point of view, there is an insignificant difference in the results from the two methods, and SINTEF normally uses the second method.

From the example in Fig. 2, it seems that the *water hammer* appears towards the beginning of the fracture closure process. Thus, pressure at water hammer is closer to ISIP.

For the *water hammer* method, the red line in Fig. 2 is filtered data to reduce the amplitude of the water hammer effect and show the base pressure. *Zero flow* is the point where flow suddenly drops to near zero.

In brief, the *water hammer* method defines the pressure towards the starting point of the fracture closure process, and the *zero flow* method defines the pressure towards the end of the fracture closure process. Normally, pressure defined by *zero flow* method is lower than pressure defined by *water hammer* method; thus, zero flow yields a minimum stress component that is lower than the one arrived at by the *water hammer* method. This is an advantage for the *zero flow* method in the hydropower industry, as it brings a somewhat higher factor of safety for the design of the project. The *zero flow* and *water hammer* methods clearly differ from the methods listed in Table 1, as the determination of the shut-in pressure is directly based on events obtained in the pressure–/flow–/time plot. The shut-in pressure is identified directly on the logged data during the test, rather than being a graphic-based interpretation.

To demonstrate the procedure of defining the shut-in pressure using the two SINTEF methods, the subsequent chapters describe laboratory and in-situ tests to show results

Fig. 2 *Water hammer* and *zero flow* methods
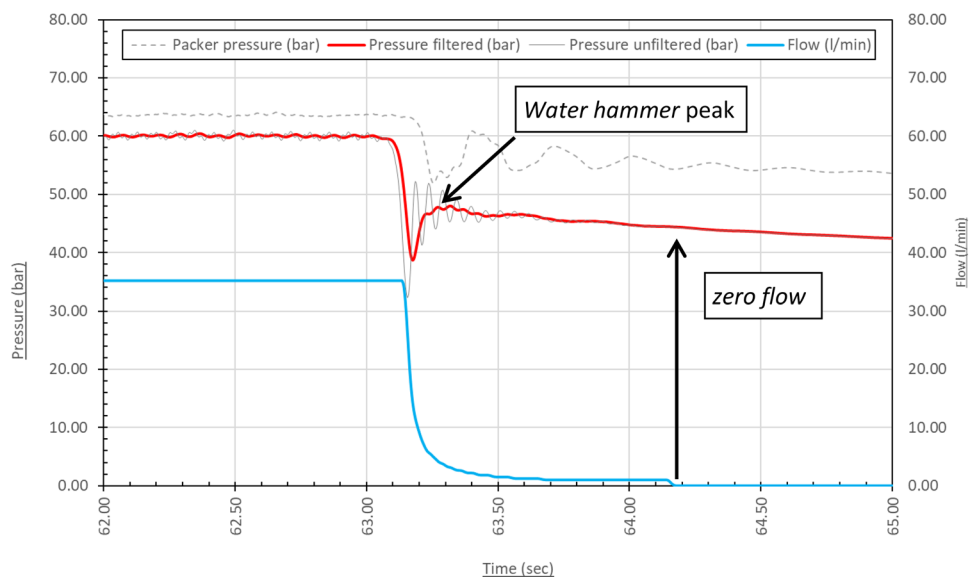
from logged data, and the interpretation process for identifying shut-in pressure.

4 Laboratory Test for Artificially Hydraulic Fracturing in SINTEF

The first demonstration of defining shut-in pressure in HF test is through a series of laboratory tests performed at the SINTEF laboratory. Equipment and procedure for the tests are described in the following sub-chapters.

4.1 Description of Equipment and Test Device

There could be several ways to artificially simulate the HF effect at the laboratory scale, such as using rock blocks (Guo et al. 1993), or commercial concrete, custom concrete, granite, acrylic, and limestone (Frash 2014).

For this laboratory test, SINTEF has applied a steel pipe and spring valve. The thick steel pipe represents an ideal wall of a drill hole in a hard intact rock. The spring valve represents an ideal elastic fracture in the way that (a) valve opens when water pressure exceeds a pre-set limit and it is closed when water pressure retracts, and (b) when closed, the valve goes back to initial position with 100% tightness. In addition to that, it is quite simple to adjust valve pressure to different values to perform the HF tests at different pressure levels. The configuration for the main components of the test is as shown in Fig. 3, and a short description of the individual elements of the testing device follows below:

- Steel pipe: outer diameter of 100 mm, thickness of 10 mm and length of 4000 mm.
- Conventional double packer for HF test. Packer elements with 1.0 m long seal length and a diameter of 70 mm. The test section is 1.0 m long.
- Spring valve: The valve will be opened when the water pressure in the test section exceeds the pressure limit of

the valve. After performing shut-in, the flow continues for a whilst causing the water pressure in the test section to decrease to a certain level when the valve closes. The valve opens and closes similar to fracture opening/closure in the rock mass. Thus, valve closing pressure is similar to shut-in pressure in rock.

- Tests with three "valve closing limits" were used: "25 bar", "50 bar" and "75 bar". The same valve was used and the "valve pressure limits" were adjusted accordingly using a pressure adjustment button.
- Pressure and flow metres were installed to log the pressure in the test section and the discharge in the system. Pressure gauge 1 and flowmeter were installed in a standard control box with flow shut-in device. Pressure gauge 2 was installed to the valve and used only for exact recording of the opening and closing pressure of the spring valve.
- Data sampling was made with a high-frequency data acquisition system. A sampling rate of 50 Hz with use of a Bessel low-pass filter of 10 Hz was sufficient to obtain crucial parameters for the *water hammer* method. Sample rates between 1000 and 10 Hz and low-pass filters were tried to see the effects and result of the water hammer. For the *zero flow* method, a sampling rate of 10 Hz and 5 Hz Bessel low-pass filter was sufficient to obtain crucial parameters.
- All data sampling was performed with high-precision 24-bit analogue-to-digital measuring amplifier with simultaneous reading of all measuring channels. The measuring accuracy is within a margin of 0.05%
- The pressure was recorded with use of absolute pressure transducer with a measuring range of 500 bars and an accuracy class 0.3%. Significant number is 0.1.
- The flowmeters used have a range from 0.1 to 35 l/min. Flow under 0.1 l/min is considered zero flow. Significant number is 0.1.
- The system was calibrated before use.

Fig. 3 Schematic layout of laboratory equipment for the simulation of a HF test
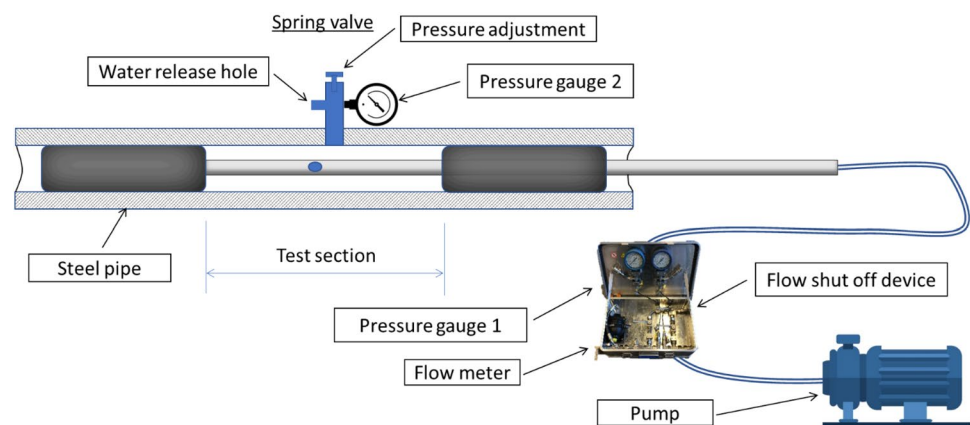
Fig. 4 Step flow test to define valve opening and closing pressure ("75 bar")
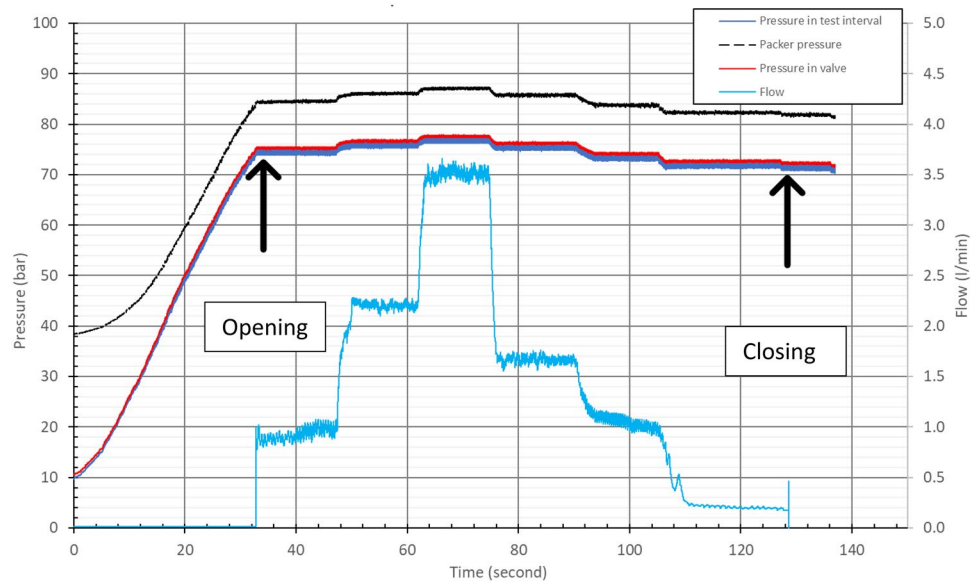
To carry out the test, the first step is to set and check the "valve pressure limit" according to the procedure as follows:

- Step 1: Manually set the valve to the intended pressure limits (25, 50 and 75 bar). This pressure is a rough control, so that the pressure limits are as close as possible to the target values (25, 50 and 75 bar). A more accurate identification of the pressure limits will be carried out in step 2.
- Step 2: Using the step flow test to identify the actual opening and closing pressure of the valve.

Examples of logged data of Step 2 are presented in Fig. 4. It is found that the opening and closing pressures were not the same for each of the tests. For each particular test presented in this paper, the actual opening and closing pressures are:

- "25 bar": Valve opening at pressure of 24.4 bar, and closing at 23.2 bar.
- "50 bar": Valve opening at pressure of 51.8 bar, and closing at 45.9 bar.
- "75 bar": Valve opening at pressure of 75.5 bar, and closing at 71.5 bar.

To identify the exact time of opening and closing, the flow metre is used to monitor when water starts flowing through the spring valve. Visual observation of the "water release hole" confirms correct timing of the spring valve opening and closure. At the time of spring valve opening and closing, the pressure is kept steady. The opening/closing pressures can be determined with an accuracy of less than ± 0.1 bar.

4.2 Test Results and Estimation of Shut-In Pressure

HF tests were carried out with the presented set up for approximately three levels of pressure, which are "25 bar", "50 bar" and "75 bar". The procedure for each test is as follows:

- Manually setting the valve pressure and performing "step flow test" to identify opening/closing pressure of the valve, according to the described procedure in Chapter 4.1.
- Immediately after the "step flow test", shut-in test was carried out. Data, such as pressure and flow versus time, were obtained. Each shut-in test was carried out in three cycles.
- The procedure was repeated for two other pressure levels.

The logged data of the tests are presented in Figs. 5, 6 and 7.

From the pressure versus time curve, shut-in pressure was determined applying all 12 listed methods in Table 1. This work was done for each of the three tests, with three cycles for each test. Thus, the total number of calculations was 108 calculations, resulting in 108 graphs. The results showed that no single set of data is sufficient to demonstrate all methods in a good way. Nine data sets from SINTEF's laboratory tests showed that it was not possible to obtain "good-graphs" as presented in their original publications for all methods. This became evident for the following: method no. 2, no. 3, no. 6 and no. 10 (method numbers are shown in Table 1). Examples of some selected graphs of existing methods are presented in Figs. 8 and 9. All results are summarised numerically in Table 2 and graphically in Figs. 10, 11 and 12.

Fig. 5 Shut-in test for pressure level "25 bar"
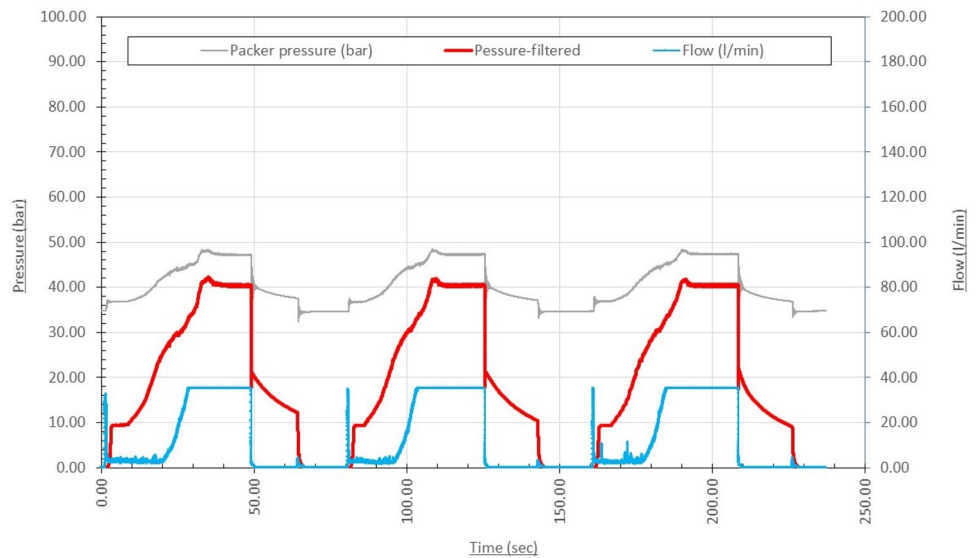
Fig. 6 Shut-in test for pressure level "50 bar"
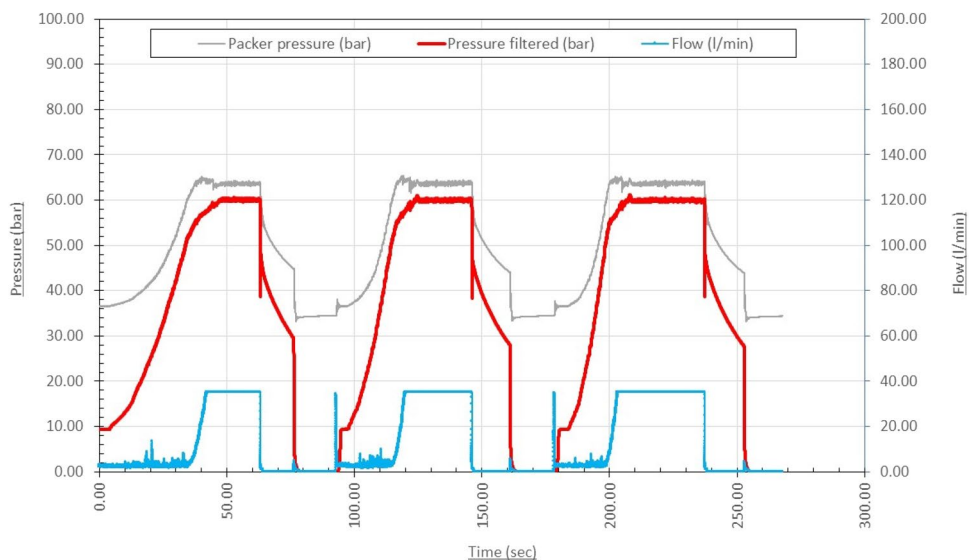
For comparison, the SINTEF methods were also applied to estimate the shut-in pressure for all tests and cycles. As a demonstration of using SINTEF methods, the results for the "50 bar" test, cycle 1 is presented in Fig. 9. As described earlier, SINTEF uses *zero flow* and *water hammer* effects to identify shut-in pressure. According to the SINTEF methods, two events can be considered to identify shut-in pressure. The events and additional comments are as follows:

- At approximately 63.25 s: This is the second peak of the *water hammer* and the data are already filtered. Thus, pressure in the test section at this point can be considered as the shut-in pressure. The shut-in pressure can be read directly on the graph as 47.5 bar.

- *Zero flow* appears at approximately 64.20 s. Thus, pressure in the test section at this time can be considered as the shut-in pressure. The shut-in pressure can be read directly on the graph as 44.5 bar.

- The *Water hammer* method is preferred when using downhole pressure transducers, where the pressure is logged directly in the test section. With this arrangement, the impact from hydraulic friction along the pipe is excluded.

- In the situation where the flow is measured only outside/at the top of the drill hole, the *zero flow* method is not a preferred method when testing in long/deep hole (more than 100 m)
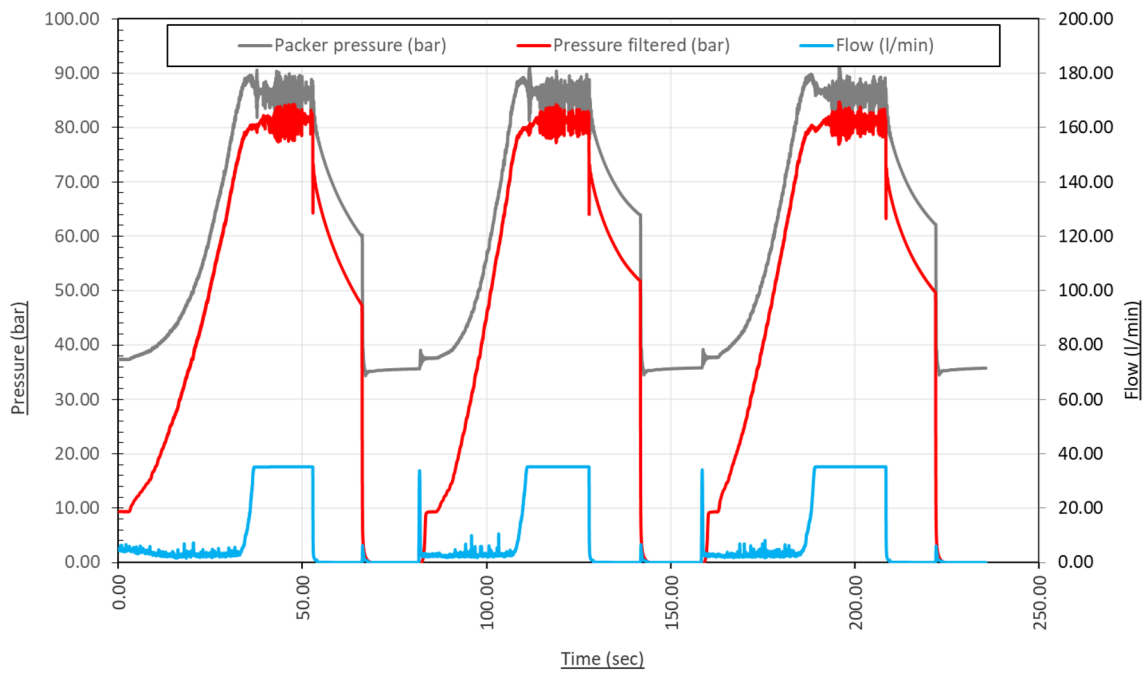
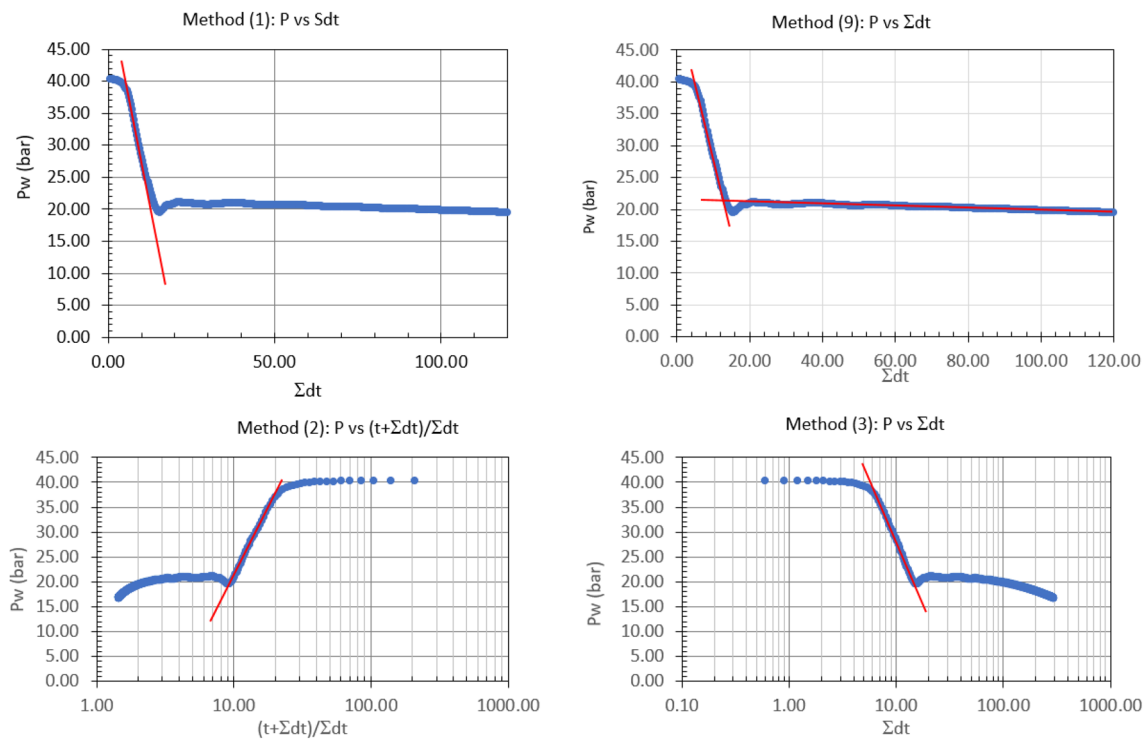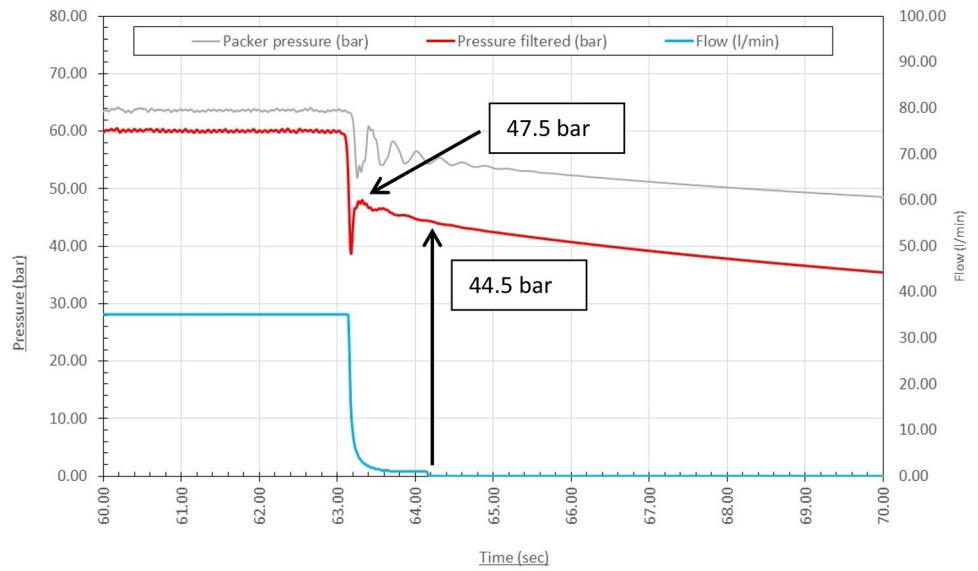**Fig. 7** Shut-in test for pressure level "75 bar"

Fig. 8 Results of shut-in pressure calculation in "25 bar" tests, cycle 2 for some selected methods

Fig. 9 Shut-in pressure identification with the SINTEF methods in "50 bar" test, cycle 1

Table 2 Calculations of the shut-in pressure based on data from HF tests in SINTEF laboratory

| Methods	Test 1—"25 bar"			Test 2—"50 bar"			Test 3—"75 bar"		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
(1) Tangential divergence or inflection	21.7	22.5	23.0	46.4	47.1	46.6	71.6	71.0	72.4
(2) P_w versus. $\log((t+Dt)/t)$	20.6	20.0	21.3	44.5	44.0	44.7	71.5	70.8	71.2
(3) P_w versus. $\log(t)$	20.0	20.0	21.3	44.4	44.1	44.1	72.9	70.8	71.2
(4) $\log(P_w - P_a)$ versus. t (Muskat method)	21.7	21.7	24.1	48.2	48.2	48.2	73.8	74.2	73.1
(5) $\log(P_w)$ versus. $\log(t)$	20.0	21.0	20.0	47.7	47.3	47.1	72.5	71.0	71.5
(6) dP_w/dt versus. P_w	21.0	21.0	20.6	NA	NA	NA	NA	NA	NA
(7) P_w versus. ÖDt	20.0	20.0	21.3	44.4	44.0	44.1	72.9	70.8	71.5
(8) Maximum curvature	19.8	20.0	20.8	47.4	47.2	47.0	72.7	72.5	71.9
(9) Tangent intersection	20.6	21.0	21.6	46.9	47.1	47.1	71.3	72.4	70.9
(10) $P–Q$ method	20.1	20.3	20.0	44.5	44.6	44.8	68.1	69.2	68.2
(11) Exponential pressure decay	20.9	21.3	21.4	41.7	46.6	46.8	71.7	72.4	71.4
(12) Bilinear pressure decay rate	21.2	19.1	19.0	41.4	36.1	56.2	70.0	70.5	76.6
(13) SINTEF zero flow	20.1	20.4	19.8	44.5	44.6	44.8	67.9	69.1	68.1
(14) SINTEF water hammer	20.8	21.0	20.5	47.5	47.6	47.2	73.1	73.6	72.0

In this test programme, data obtained from three test levels were analysed, comparing the SINTEF methods with 12 other methods as shown in Table 2 and Figs. 10, 11, 12. From the comparison, the following conclusions can be made:

- In all the test cycles, the SINTEF methods produced results comparable to the other methods.
- All methods (except the bilinear pressure decay rate—method no. 12) estimated shut-in pressures within ± 10 to ± 15% of accuracy to the valve closing pressure.
- In individual tests, some of the methods such as dP_w/dt versus. P_w (method no. 6), exponential pressure decay (method no. 11) and bilinear pressure decay rate (method

no. 12) yielded much lower results than the general picture from the others.

- It seems that the *water hammer* method always gives higher shut-in pressure than the *zero flow* method. The reason for this is that the water hammer effect appears earlier than the zero flow. Thus, pressure in the test section is higher at the time of water hammer.
- The *zero flow* method seems giving lower limit of the shut-in pressure.
- Results of the *zero flow* method are similar to the P–Q method in most cases.
- The SINTEF methods yielded results comparable to the other interpretation methods.
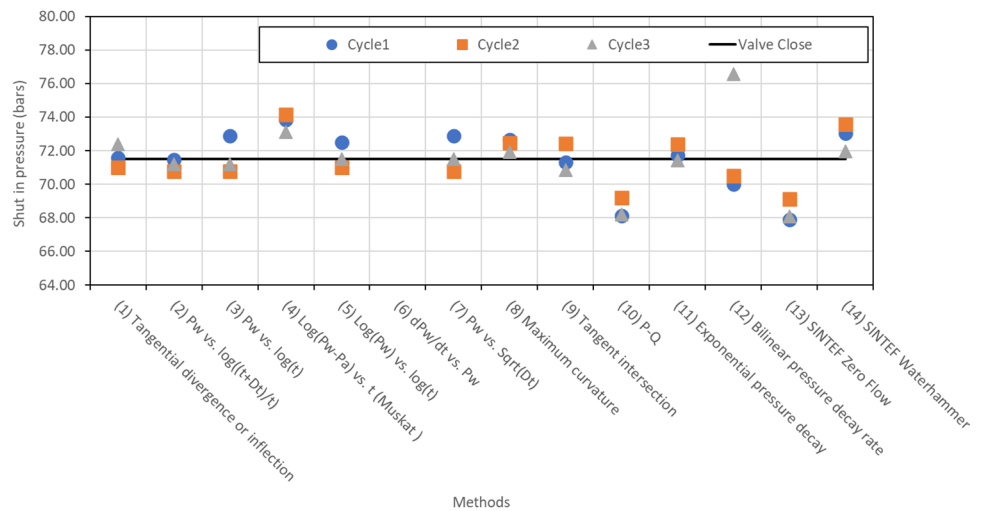
Fig. 10 Results of shut-in pressure calculation in "25 bar" tests, in comparison to the closing pressure of the spring valve
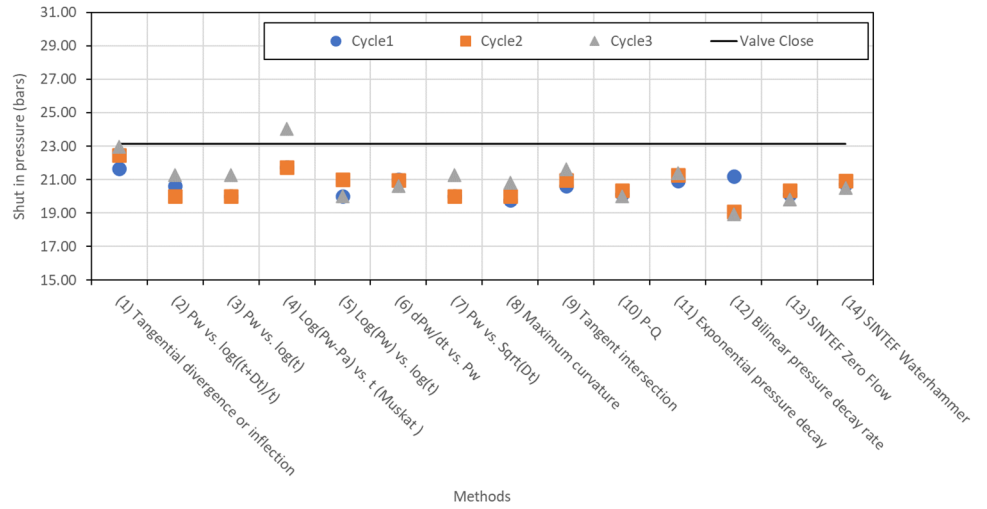
Fig. 11 Results of shut-in pressure calculation in "50 bar" tests in comparison to the closing pressure of the spring valve
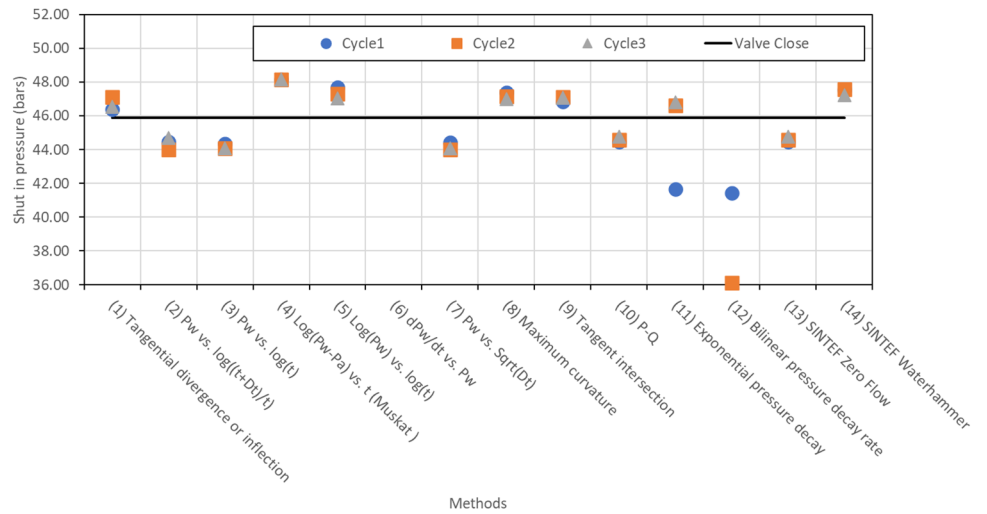
Fig. 12 Results of shut-in pressure calculation in "75 bar" tests in comparison to the closing pressure of the spring valve

During the laboratory test performance, a concern was raised whether the observed *water hammer* was caused by the shut-off device and not by the closing of the valve. To clarify this concern, another series of tests was performed on the same arrangement and devices. This time, the spring in the valve was removed, so that the valve did not close at any pressure. Several tests were performed, and all obtained results showed no *water hammer* effect. From the second series of tests, it was concluded that the observed *water hammer* in the first series of tests was from the closing of the valve, confirming the initial theory.

5 In Situ Hydraulic Fracturing at Løkjelsvatn Hydropower Project

The power plant "Løkjelsvatn Kraftverk" is located close to the Etne town in the Vestland county, Norway. Løkjelsvatn power plant is currently under construction and will have an installation capacity of 60 MW, and an average annual production of about 160 GWh.

The waterway system of the project consists of approximately 1 km headrace tunnel and 2.5 km tailrace tunnel, and an underground powerhouse, as shown in Fig. 13. The headrace tunnel is designed according to the Norwegian practise of unlined pressure tunnels. The tunnel is supported by rock bolts and shotcrete where required. Concrete lining is used only in extremely poor rock mass conditions such as fault or weakness zone.

The Norwegian concept with unlined pressure tunnel has proven to be economic, and cost and construction time efficient. However, one detail to be focussed is the location of the concrete plug upstream of the underground powerhouse. The concrete plug represents the transition from unlined headrace tunnel to steel-lined section approaching the powerhouse. This implies that the location of concrete plug is a decisive for the length of the steel lining, which has a strong impact on the project on the cost and construction time.

As the location of the concrete plug represents the transition from unlined to lined tunnel, the following considerations must be made:

- The concrete is placed as close to the powerhouse as possible to keep the length of steel lining at a minimum.
- The concrete plug is placed in competent rock mass with low permeability.
- On the upstream side of the concrete plug, the rock stress must be larger than water pressure to prevent hydraulic jacking, which opens existing joints/discontinuities in the rock mass and further leads to excessive water leakage.

To make sure that the required conditions are met, the minor principal stress is determined and compared with the static water pressure at the location.

Following the common practise in Norway, a thorough rock stress measurement campaign was carried out at the planned location of the concrete plug for Løkjelsvatn hydropower project. Location for the rock stress investigation is shown in Fig. 13. The rock stress measurements were carried out as follows:

- Step 1: A 3D overcoring stress measurement was carried out to have a complete picture (magnitude and orientation) of all principal stresses. For 3D overcoring, the stresses are calculated from the measured strains and the elastic properties of the rock samples. Stresses obtained by this method are indirect and may have uncertainties, and measured with only 10^{-3} to 10^{-2} m^3 of involved rock volume (Ljunggren et al. 2003). Thus, to acquire more direct information of the rock stress condition with much larger involved rock volume, a second step with HF stress measurement method was carried out.
- Step 2: Six drill holes are drilled to approximately 30 m for HF test. The drill holes were oriented parallel to the orientation of intermediate principal stress (obtained from the first step). Several tests were carried out in each drill hole at different depths.

The layout of the stress measurements is shown in Fig. 14. As can be seen from the figure, at the location of drill hole H4, rock stress was measured by both 3D and HF methods. Thus, this location provides a good opportunity for comparison of the shut-in pressure obtained from HF tests with the value of minor principal stress obtained from 3D measurement.

In the following, the data from Løkjelsvatn, a real site, shall be used to demonstrate the use of the *zero flow* and the *water hammer* methods.

5.1 Equipment and Test Procedure

Standard equipment was used for the tests. A 57 mm inflatable double packer system (straddle packer), through which a water flow pipe runs, is used to isolate a section of the hole, enabling a test section to be pressurised. Pressurised water is used to expand the packers and thereby seal the test section. The initial packer setting pressure is normally set to 35 bar. If the pressure in the test section approaches the packer pressure, the packer pressure must be increased to prevent water from bypassing the packers. Normally the packer setting pressure is held approximately 20 bars higher than the pressure in the test section. The packers are separated by spacers, which make the test section
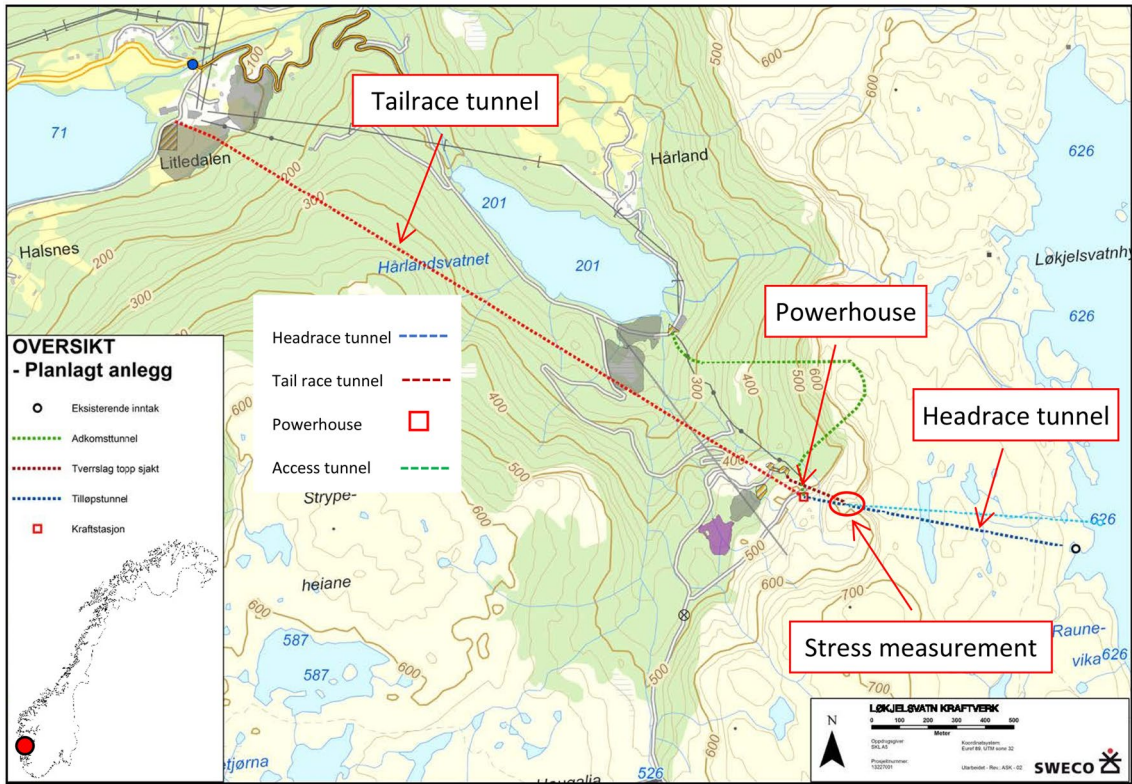
Fig. 13 Layout of the Løkjelsvatn hydropower project (NVE 2018) and location of the stress measurement

approximately 1.0 m long. To achieve fracturing in the rock mass and not jacking of an existing joint, the test section must not have any discontinuities, such as cracks or joints. Leakage tests are performed before each test to control that the test section is placed in intact rock.

Pressure transducers for measurement of fluid and packer pressures are located at the surface. A flow metre is also located on surface and is used to record fluid flow over time. Pressure and flow are continuously recorded during the testing and all data sampling was performed with high-precision

Fig. 14 Arrangement of the stress measurement at the Løkjelsvatn hydropower project
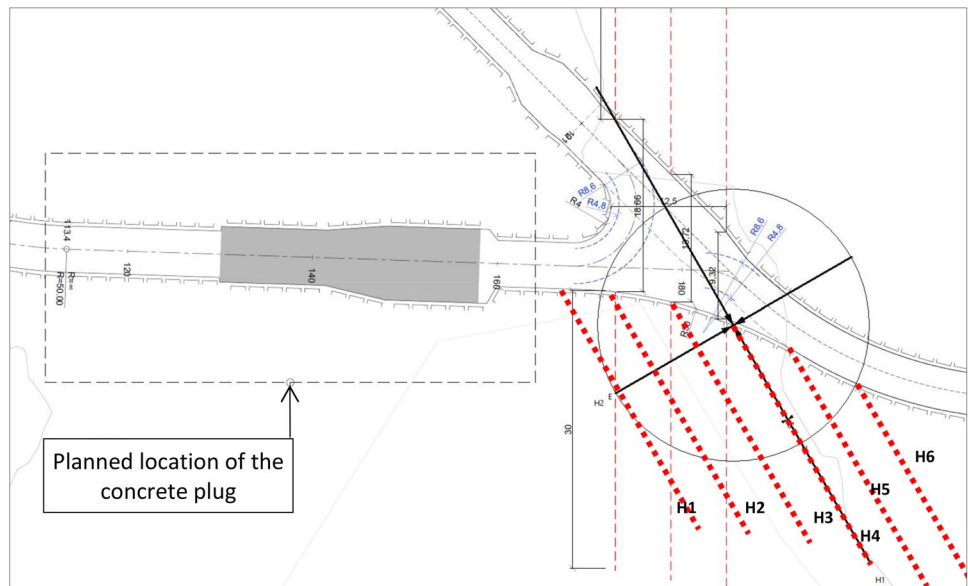
Table 3 Estimation of the shut-in pressure with *zero flow* and *water hammer* methods for HF tests in drill hole H4 at Løkjelsvatn hydropower project

Test number and method	HF test (bar)			Sigma 3 (MPa) (3D measurement)	
	Cycle 1	Cycle 2	Cycle 3		
Test 1 at depth 28.2 m					
SINTEF zero flow		83.9	80.9	84.3	9.4 ± 1.0
SINTEF water hammer		95.0	94.0	93.3	9.4 ± 1.0
Test 2 at depth 25.2 m					
SINTEF zero flow		80.9	75.8	73.3	9.4 ± 1.0
SINTEF water hammer		89.1	83.4	81.6	9.4 ± 1.0
Test 3 at depth 22.2 m					
SINTEF zero flow		81.4	80.8	83.8	9.4 ± 1.0
SINTEF water hammer		89.5	89.8	90.6	9.4 ± 1.0
Test 4 at depth 19.2 m					
SINTEF zero flow		77.9	91.1	102.0	9.4 ± 1.0
SINTEF water hammer	? (*)	90.7	? (*)		9.4 ± 1.0

(*) Measurement equipment was not optimised (ten times/sec) for obtaining water hammer effect in a challenged rock mass situation

24-bit analogue-to-digital measuring amplifier with simultaneous reading of all measuring channels. The same system is used in the laboratory tests.

For the HF method, SINTEF used standard procedures as described in ASTM D 4645–04 (ASTM 2004), and ISRM suggested methods for rock stress estimation—Part 3: hydraulic fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF) (ISRM 2003). The test procedure has already been briefly described in Chapter 1 in this paper.

5.2 Estimation of Shut-In Pressure and Comparison with 3D Measurement

In drill hole H4, four HF tests were carried out at depths 28.2, 25.2, 22.2 and 19.2 m. The tests were named as Test 1, 2, 3 and 4, respectively, as shown in Table 3. As an example, one of the tests is presented graphically in Fig. 15. There were 3 cycles for each test, resulting in a total of 12 cycles. The obtained data from these 12 cycles were used as input to estimate the shut-in pressure.

Interpretation of the test data was performed with the *zero flow* and *water hammer* methods as previously described in Fig. 9. As for detailed demonstration, Figs. 16, 17, 18 graphically present the way to identify the shut-in pressure with the SINTEF methods for Test 2 (all three cycles).

The shut-in pressure was also interpreted applying 12 existing methods for comparison with the 2 new methods. Some selected graphs of the interpretation are presented in Fig. 19. It is noted from the figure that to get a reliable result for the interpretation, the density and the distribution of the data (the rounded dots in the figure) are very important. Even distribution of the dots to form a smooth curve would be ideal for constructing good tangential or best-fit lines and obtaining a reliable shut-in pressure. In reality (as the case at Løkjelsvatn), rock mass conditions cause a lot of disturbances to the data. It is rarely to get a smooth curve of data. Thus, interpretation of shut-in pressure for an in situ test using 12 existing methods often involves personal judgements and certain deviations.

With such complications in mind, a careful data processing and interpretation of the shut-in pressure for the 4 in situ tests was made and the results were obtained for the 12 existing methods. The obtained results in comparison with SINTEF
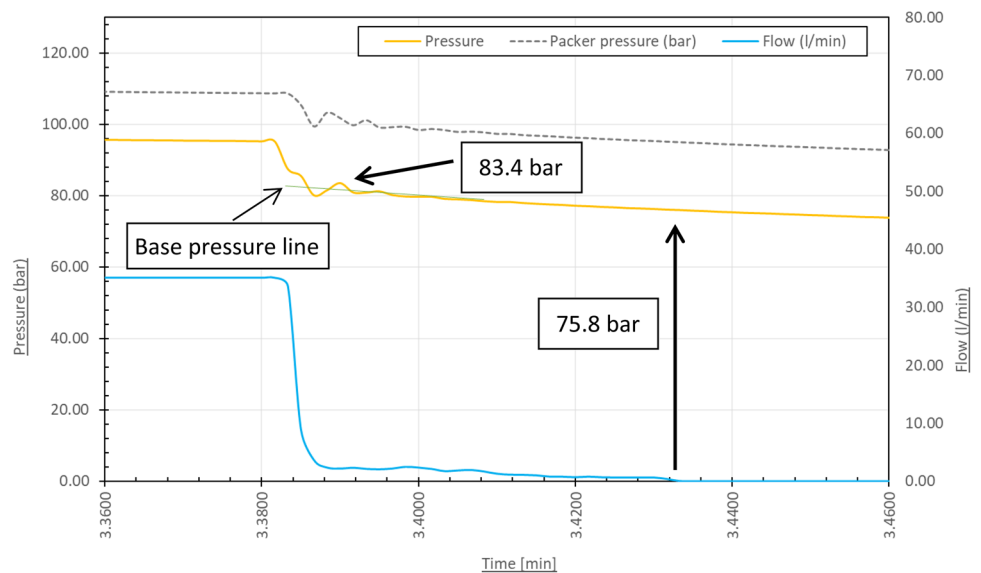
Fig. 15 HF tests in drill hole H4—Test 3, at Løkjelsvatn hydropower project
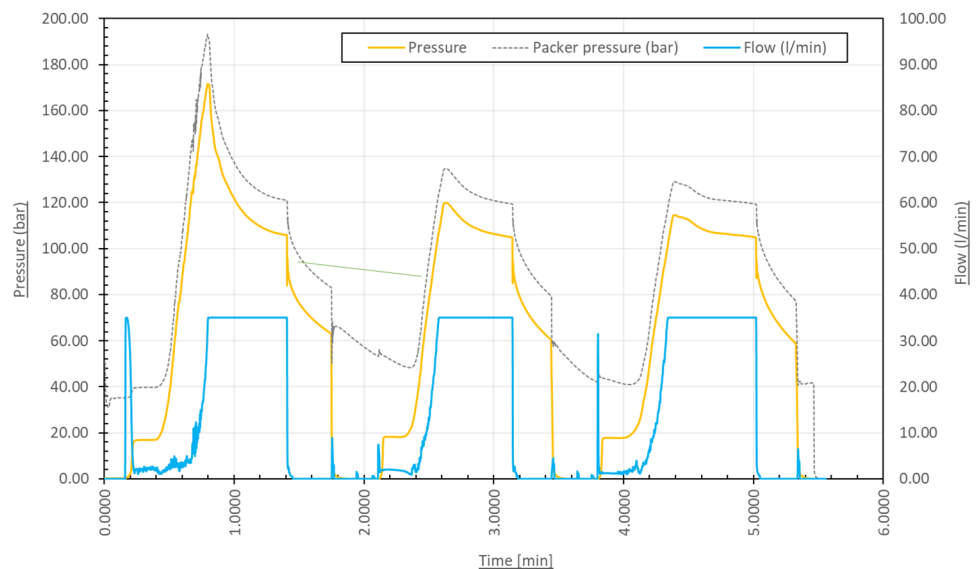
Fig. 16 HF test at Løkjelsvatn hydropower project—Test 2, cycle 1: shut-in pressure with the SINTEF methods
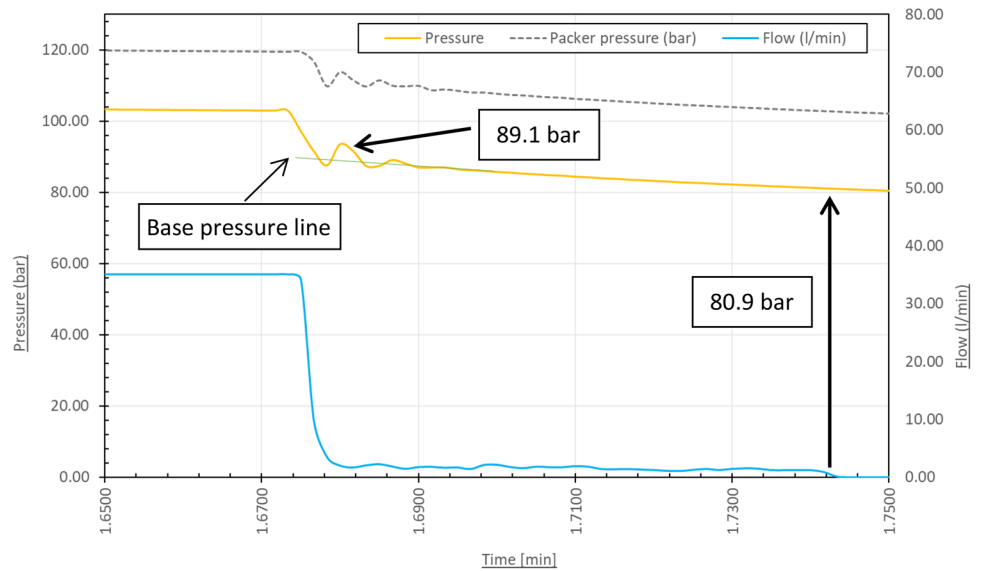
Fig. 17 HF test at Løkjelsvatn hydropower project—Test 2, cycle 2: shut-in pressure with the SINTEF methods


methods are shown graphically in Figs. 20, 21, 22, 23. The results obtained from SINTEF methods in comparison with the results from 3D measurement are presented in Table 3.

It can be seen that the SINTEF methods provide results comparable with the 3D stress measurement. Results from SINTEF methods are also comparable with all other methods:

- In in situ Test 1: Shut-in pressure identified by the SINTEF methods is ranging from 81 to 95 bar, whilst the 3D measurement resulted in 9.4 ± 1.0 MPa (94 ± 10 bar).
- In in situ Test 2: Shut-in pressure identified by the SINTEF methods is ranging from 73 to 89 bar, whilst the 3D measurement resulted in 9.4 ± 1.0 MPa (94 ± 10 bar).

Fig. 18 HF test at Løkjelsvatn hydropower project—Test 2, cycle 3: shut-in pressure with the SINTEF methods
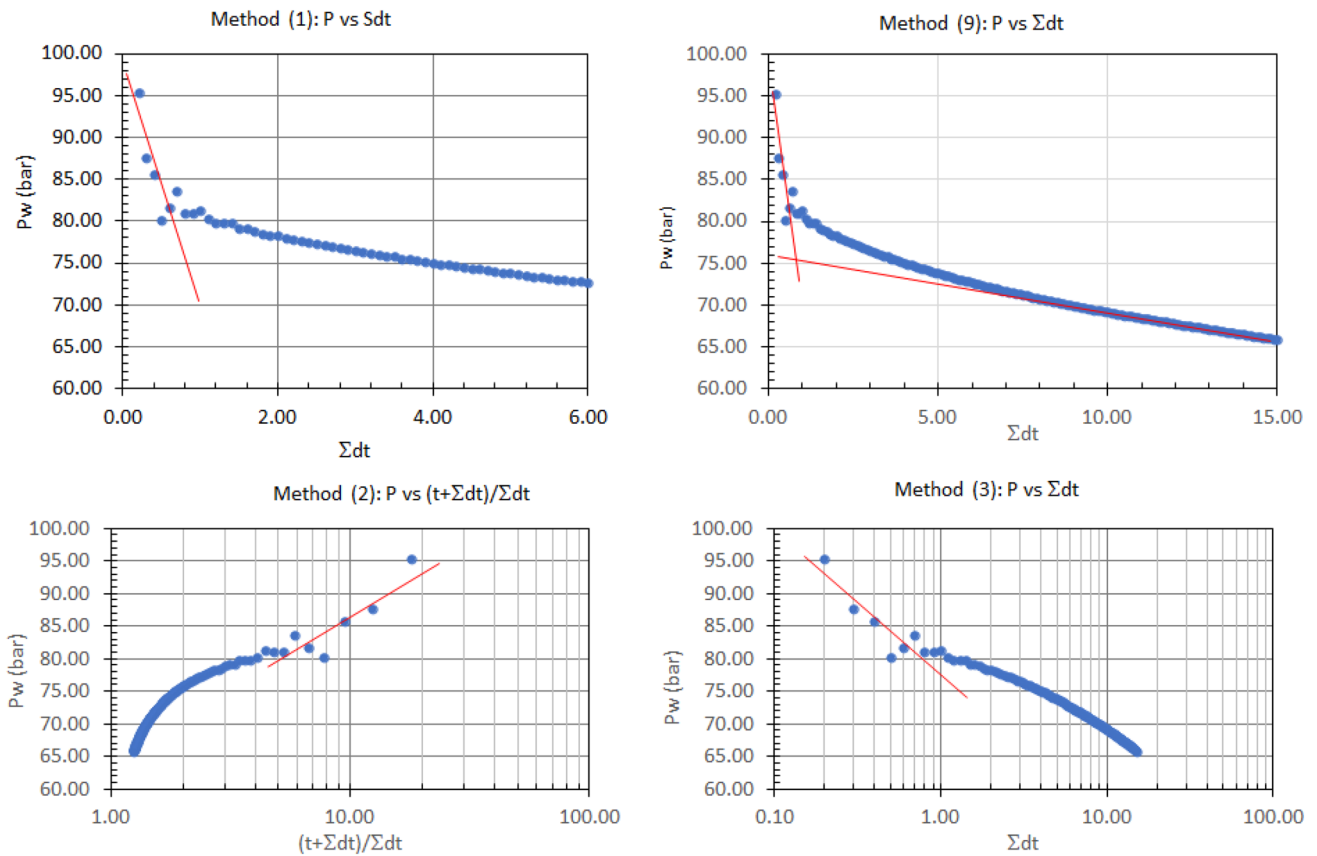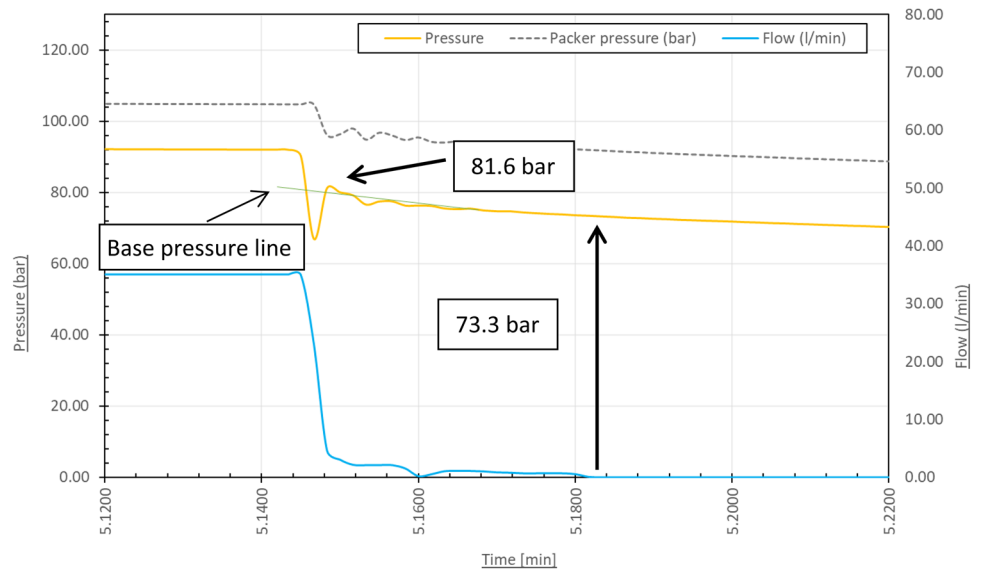

Fig. 19 Some results of shut-in pressure calculation in Tests 2, cycle 2 for some selected methods

- In in situ Test 3: Shut-in pressure identified by the SINTEF methods is ranging from 81 to 91 bar, whilst the 3D measurement resulted in 9.4 ± 1.0 MPa (94 ± 10 bar).

- In in situ Test 4: Shut-in pressure identified by the SINTEF methods is ranging from 78 to 102 bar, whilst the 3D measurement resulted in 9.4 ± 1.0 MPa (94 ± 10 bar).

Fig. 20 Results from estimation of the shut-in for all methods, for drill hole H4—Test 1 at Løkjelsvatn hydropower project in comparison with 3D stress measurement. (Lower and upper lines represent the ± 1.0 MPa in the result of the 3D measurement)
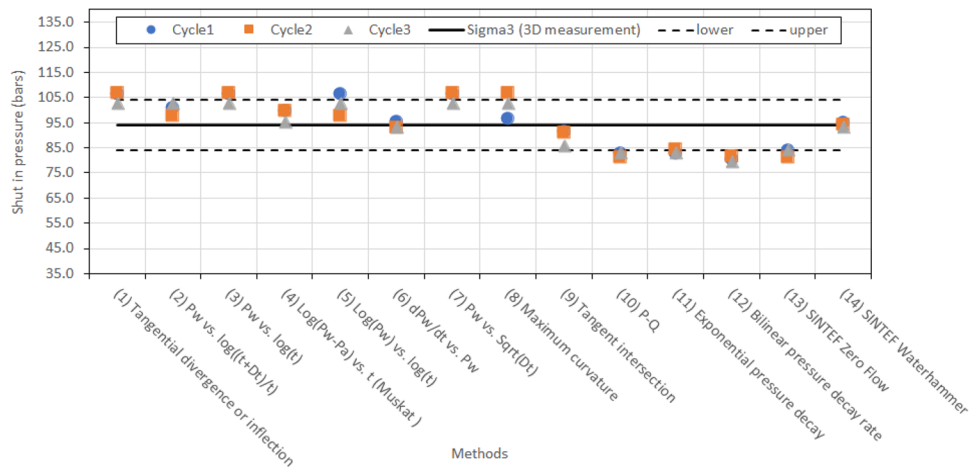
Fig. 21 Results from estimation of the shut-in for all methods, for drill hole H4—Test 2 at Løkjelsvatn hydropower project in comparison with 3D stress measurement. (Lower and upper lines represent the ± 1.0 MPa in the result of the 3D measurement)
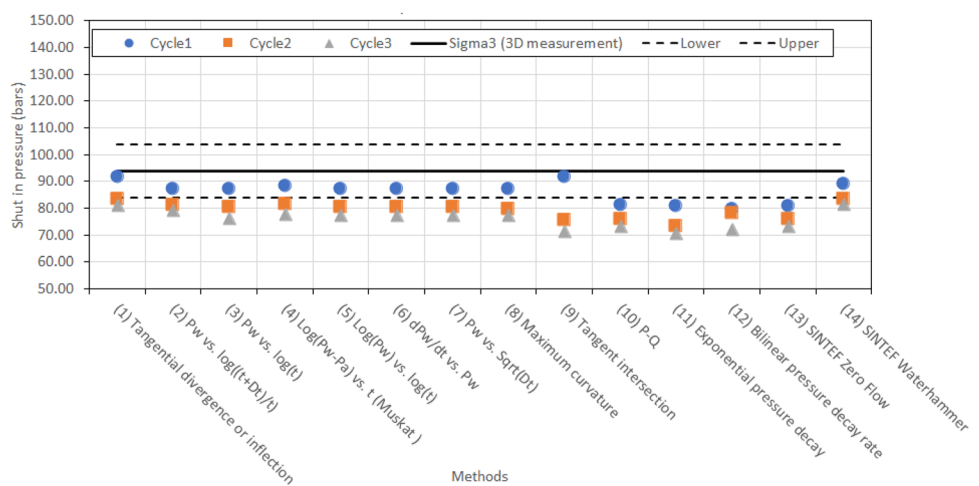
Fig. 22 Results from estimation of the shut-in for all methods, for drill hole H4—Test 3 at Løkjelsvatn hydropower project in comparison with 3D stress measurement. (Lower and upper lines represent the ± 1.0 MPa in the result of the 3D measurement)
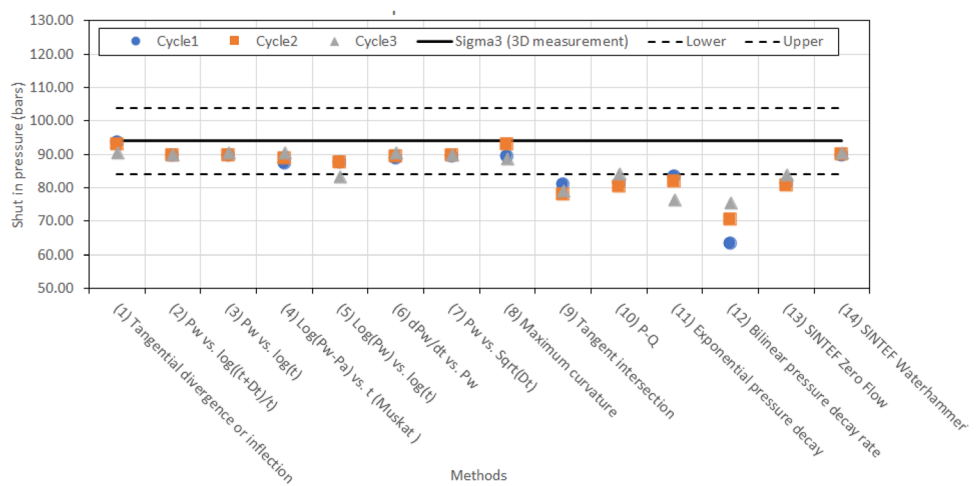
- Shut-in pressure identified by the *zero flow* method is lower than most of other methods, and similar results are obtained by the P–Q method.
- Shut-in pressure identified by the *water hammer* method is in the same range with most of other methods.

Thus, from the comparison, it can be stated that the SINTEF methods can be used as alternative methods for identifying shut-in pressure in HF tests.

Fig. 23 Results from estimation of the shut-in for all methods, for drill hole H4—Test 4 at Løkjelsvatn hydropower project in comparison with 3D stress measurement. (Lower and upper lines represent the ± 1.0 MPa in the result of the 3D measurement)
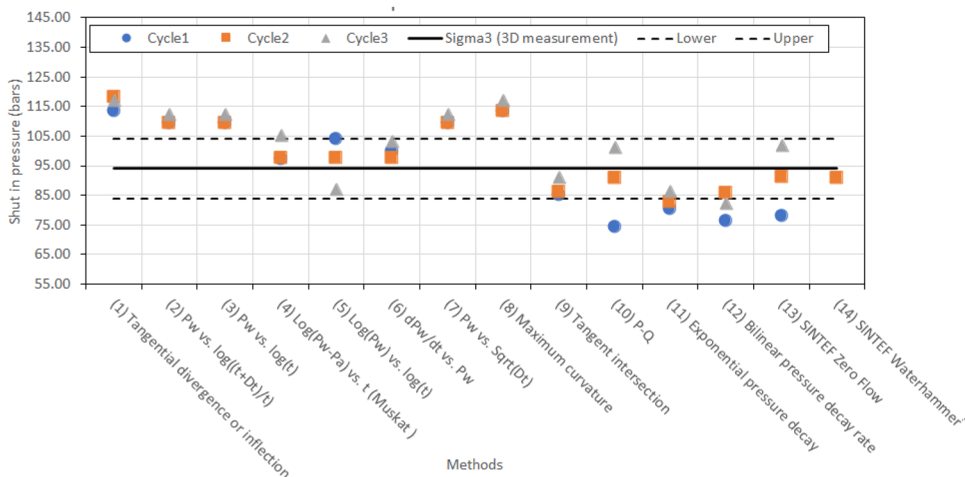
**Fig. 24** Pressure transient in a laboratory test
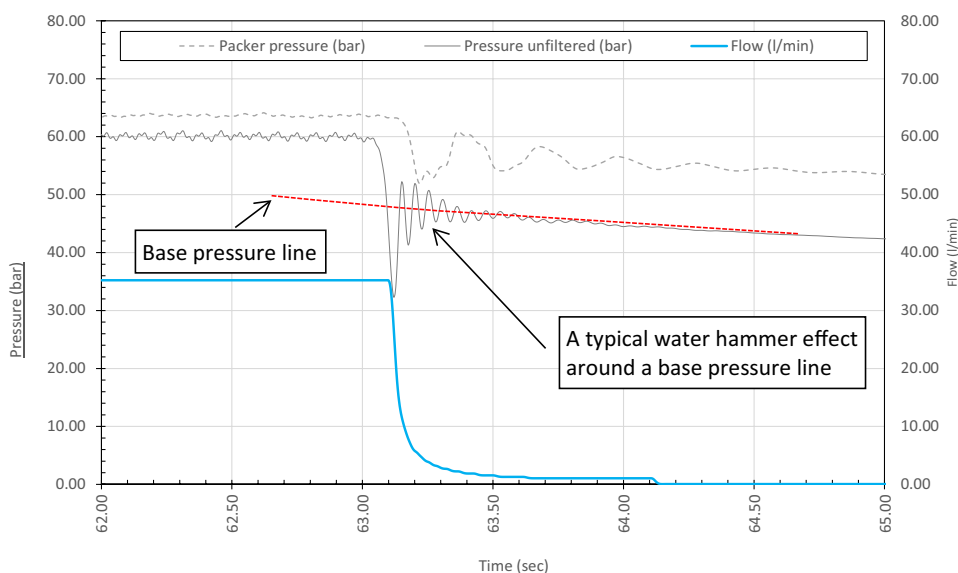
6 Discussion

Laboratory and in situ tests presented in this paper demonstrate that hydraulic fracturing in hard rock conditions is a complicated process. The fracture closure or the fracture shut-in in a HF test should be considered as a process with certain time duration rather than an instant event. During this closure process, the ISIP seems to correspond to the start of the process, and the closure pressure seems to correspond to its termination.

The evaluation of the shut-in pressure using the 12 described methods provide pressure results at different point in time during the closure process. There was no concrete evidence to convincingly demonstrate that the resulted pressure is corresponding to each specific point of time during the fracture closure process. Pressure at the end of fracture opening (probably right before the shut-in process) is also defined as shut-in pressure by some authors (Hayashi

and Haimson 1991). It is, however, very challenging to physically and accurately define a point in time when the opening process of the fracture ceases.

In fact, the pressure transient from the moment that a hydrofracture starts to close is a complicated process. Spring valve tests at SINTEF showed that this transient could be a water hammer effect. As mentioned in Chapter 4.1, the spring valve simulates a perfect elastic facture with an ideal elastic behaviour and no leakage. Results from the laboratory tests showed that the pressure transient during shut-in process is a perfect water hammer effect with typical sine-type fluctuation—as shown in Fig. 24. The starting point of the water hammer can be considered as the starting point of the shut-in process, and the pressure at this moment is ISIP. However, defining the starting point of the water hammer could be complicated. In the *water hammer* method, for simplification, SINTEF

Fig. 25 Pressure transient in an in situ test
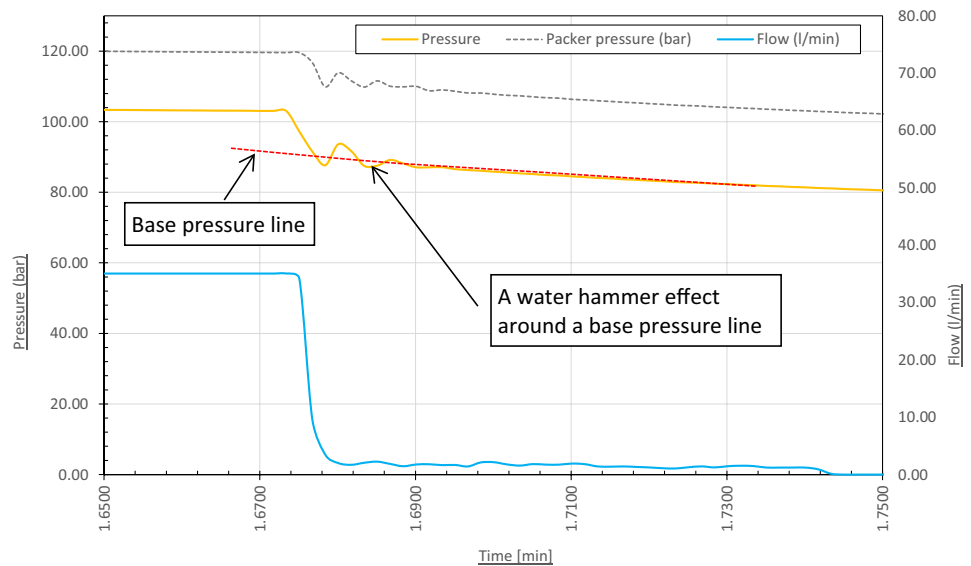
uses an approximate way, as presented earlier, to estimate shut-in pressure.

In an in situ test, the pressure transient could also be a water hammer effect. However, water hammer effect in this situation is more complicated, as the hydrofracture may not be perfectly elastic and the shape of the hydrofracture may be complicated with an irregular inlet that could have an impact on the head loss. With such disturbances from in situ rock, the water hammer effect is not as perfect as it was in the laboratory case, as shown in Fig. 25.

In brief, estimating shut-in pressure in a HF test is complicated and different interpretation methods may give different results. It is important to bear in mind that the fracture closure is a process with a certain duration, not a single event. Thus, when estimating shut-in pressure using different methods, the following can be concluded:

- Different methods may result in slightly different pressures, as such results may correspond to different points in time during the fracture closure process. Without concrete evidence of time, the estimated pressures could be somewhere between ISIP and closure pressure.
- Pressure transient during shut-in process seems to be a water hammer effect. This effect is site dependent as it depends on a combination of rock behaviour, fracture shape and characteristic, and the stress acting normal to the fracture. This makes the characteristic of HF data different from site to site. Thus, for a specific HF test at a site, some interpretation methods may be more suitable than other.
- The estimated shut-in pressures must be placed in context with pressure transient during shut-in process. Depending on the use of the estimated pressure,

appropriate pressure can be selected as shut-in pressure. In hydropower industry, for example, when using the estimated pressure to design unlined tunnels and shafts, the estimated pressure towards the end of fracture closure (or shut-in) process is preferred as it brings some extra factor of safety to the design.

7 Concluding Remarks

SINTEF has developed two methods to define shut-in pressure in HF tests and both are presented in this paper, namely *zero flow* and *water hammer* methods. These methods are based on practical experience from thousands of individual in situ HF tests done by SINTEF for a wide variety of applications, such as hydropower, tunnel and cavern projects, and mining. To demonstrate the two methods, this paper presents and discusses the findings from laboratory and in situ tests.

The results of shut-in pressure determination based on these two methods were compared with 12 other methods, and it can be concluded that the results are comparable. It can be further concluded that the two SINTEF methods can be used as alternative methods for defining the shut-in pressure. The SINTEF methods enable the estimation of shut-in pressure directly from the pressure/time charts in real time on site. No additional graphical work, fitting or extrapolation is needed.

The disadvantage of the two methods is that both require high-frequency simultaneously data sampling up to 50 Hz and a proper data filtering.

Advantages of the two SINTEF methods are:

- The *water hammer* and the *zero flow* methods can be determined instantaneously after shut-in and directly from the graph logging without using fitting or extrapolation work.
- A shut-in period of 15–30 s is enough to define shut-in pressure with the SINTEF methods. There is no need to keep the shut-in over a long period (3–10 min), as for the other methods suggested by ISRM.
- The SINTEF methods are quick and flexible.
- After shut-in, both pressure and flow curves drop instantly and produces almost vertical flow/pressure against time curves. To obtain good data for a reliable interpretation using the 12 existing methods, it would require a very high logging frequency and a smooth data curve during this period. With the two SINTEF methods, these requirements are not necessary.

Interpretation methods tested in this scheme provided comparable shut-in pressure levels. It implies that performing the tests with correct setup/equipment is much more important than selecting the method for interpretation of the shut-in pressure. Results from this research show that fracture closure (or shut-in) should be considered as a time process rather than an instant event. Pressure transient during the closure process is a water hammer effect, which is site dependent. Estimated shut-in pressure by different methods should be determined taking into consideration the fracture closure as a process and the water hammer effect.

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