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Laboratory tests for demonstrating two new methods for defining shut-in pressure in hydraulic tests for rock stress measurement

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Abstract

Hydraulic test (HF and HTPF) 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*. This paper presents laboratory tests to demonstrate these two new methods. The results are compared with other existing methods within the rock stress measurement field. These two new methods have traditionally been used in 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.

Keywords

Hydraulic fracturing of intact rock (HF), Hydraulic tests on pre-existing fractures (HTPF), Stress estimation, Hydropower.

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1 Introduction

Hydraulic test is a commonly used borehole field test method designed to assess the state of in situ stress in a rock mass, especially at great depths, where the test locations are only accessible by drillholes. The test can be divided into three groups: the hydraulic fracturing of intact rock (HF), the sleeve fracturing, and the hydraulic test on pre-existing fracture (HTPF) (Amadei and Stephansson 1997), where the HF and HTPF are the most common. It is necessary to emphasise that in this paper the term “hydraulic test” is used to cover both HF and HTPF. When mentioning HF or HTPF specifically, it will be clearly stated.

When using results from hydraulic tests for estimating in situ rock stress, the most important information obtained from the tests would be shut-in pressure. Fracture closure in hydraulic tests is a complicated process, and therefore shut-in pressure in hydraulic tests is not a straightforward parameter to obtain. Many methods have been developed by different authors to estimate shut in pressure. This paper briefly presents existing methods to define shut-in pressure and introduce two new methods. Comprehensive laboratory tests are also presented to demonstrate the two new methods and comparing the results with existing ones.

2 Shut-in pressure in hydraulic tests

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. Even though, ASTM and ISRM present the definition of shut-in pressure for HF test, but the definitions can also be used for HTPF.

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 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. 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. More detailed information of the process can be found in Trinh et al. (2023).

Estimation of the shut-in pressure is not straight forward, and many methods have been developed by different authors. Guo et al. (1993), and Amadei and Stephansson (1997) reviewed the methods currently available for interpretation shut-in pressure. The methods are summarised with original and important references in Table 1.

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

No.	Name of the methods	Reference
1	Tangential divergence or inflection method	Gronseth and Kry (1981) and Gronseth (1982).
2	*Pw* versus *log((t+Δt)/t)* method	McLennan and Roegiers (1981)
3	*Pw* versus *log(t)* method	Doe and Hustrulid (1981)
4	*Log(Pw-Pa)* versus *t* method (Muskat method)	Muskat (1937); Aamodt & Kuriyagawa (1981)
5	*Log(Pw)* versus *log(t)* method	Zoback and Haimson (1982)
6	*dPw/dt* versus *Pw* method	Tunbridge (1989)
7	*Pw* versus $\sqrt{\Delta t}$ 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)

In addition to the existing methods listed in the table, SINTEF has established two practical ways of defining shut-in pressure (Trinh et al. 2023). 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.

To better understand of the *zero flow* method, a typical test record is presented in Fig. 1. As can be seen from the figure, pump shut off induces a rapid reduction of the water flow in the system. The graph of flow versus time right after shut off is dropping almost vertically. Towards the end of this period, a very small amount of flow is still recorded in the system. Even though the amount of flow is very small, it is prolonging for a certain duration, making the flow-time graph curving and sub-horizontal within the period. Utilising the definition that "*the instantaneous shut-in pressure is as the minimum downhole injection pressure required to hold the induced crack open*" (Hayashi and Sakurai, 1989), SINTEF uses the time step when the flow is almost zero (less than 0.01 l/min) to read the pressure in the test section. This pressure is considered to be the shut-in pressure – or closure pressure to be more precise.

The second criterion for defining shut-in pressure is thus based on the observation of the *water hammer* effect. 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), as shown in Fig. 1. Analyses of this event indicate that this is caused by a *water hammer* effect in the system. It seems that shut in pressure defined by *water hammer* effect may be more corresponding to ISIP.

More detailed descriptions of the methods and how to define the shut in pressure using *zero flow* and *water hammer* methods can be found in Trinh et al. (2023).

In the next sections, laboratory tests are described to demonstrate the two new methods and comparing the results with the existing ones.

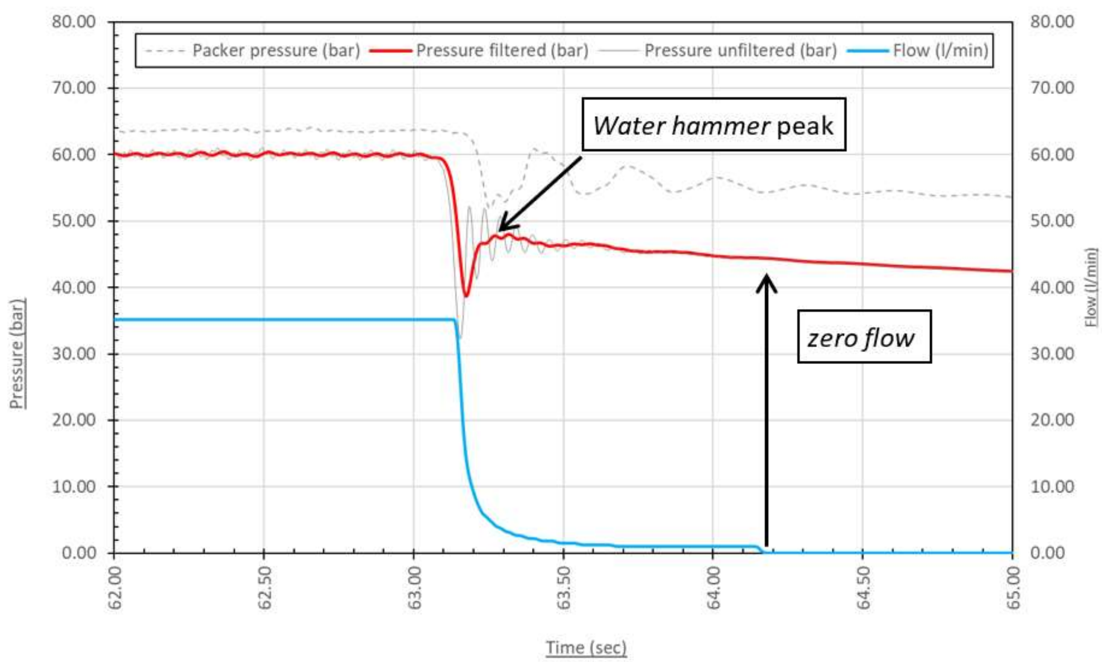

Fig. 1 *Water hammer* and *zero flow* methods.

3 Laboratory set-up

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 et al. 2014).

For this laboratory test, SINTEF has applied a steel pipe and spring valve. The thick steel pipe represents an ideal wall of a drillhole 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 closes 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 in order to perform the hydraulic tests at different pressure levels. It is also found after the test that the valve is not able to simulate the fracture break down pressure in HF tests. The spring valve behaviour as a pre-existing fracture in rock mass. Thus, the tests using this set up actually represent HTPF tests. However, the way to define shut-in pressure is similar between HF and HTPF. It means that the methods to define shut-in pressure describes in this paper can be used for both HF and HTPF.

Configuration for the main components of the test is as shown in Fig. 2, 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 while 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 by using a pressure adjustment button.
- Pressure and flow meters 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 1000-10 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 analog-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 0.1-35 l/min. Flow under 0.1 l/min are considered zero flow. Significant number is 0.1.
- The system was calibrated before use.

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.

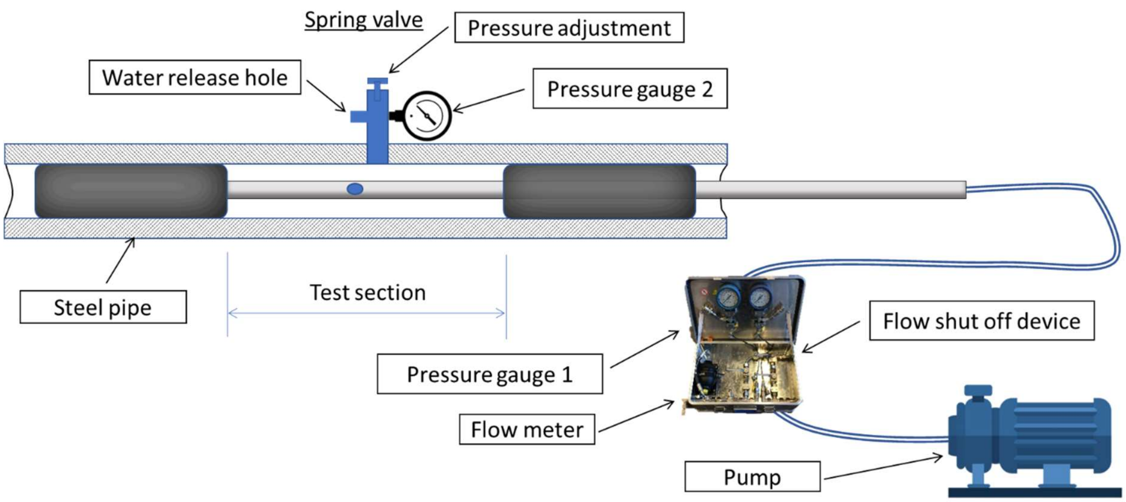

Fig. 2 Schematic layout of laboratory equipment for the simulation of a hydraulic test.

It is found through the step tests that the opening and closing pressure was 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 meter 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 Test results and comparison

HTPF 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.
- Immediately after the "step flow test", shut-in test was carried out. Data, such as pressure and flow versus time was obtained. Each shut-in test was carried out in 3 cycles.
- The procedure was repeated for two other pressure levels.

The logged data of one of the tests is presented in Fig. 3.

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). More detailed information of the shut-in pressure estimations can be seen in Trinh et al. (2023).

For comparison, the SINTEF methods were also applied to estimate the shut-in pressure for all tests and cycles. In this test program, data obtained from 3 test levels were analysed, comparing the SINTEF methods with 12 other methods as shown in Figs. 4 to 6.

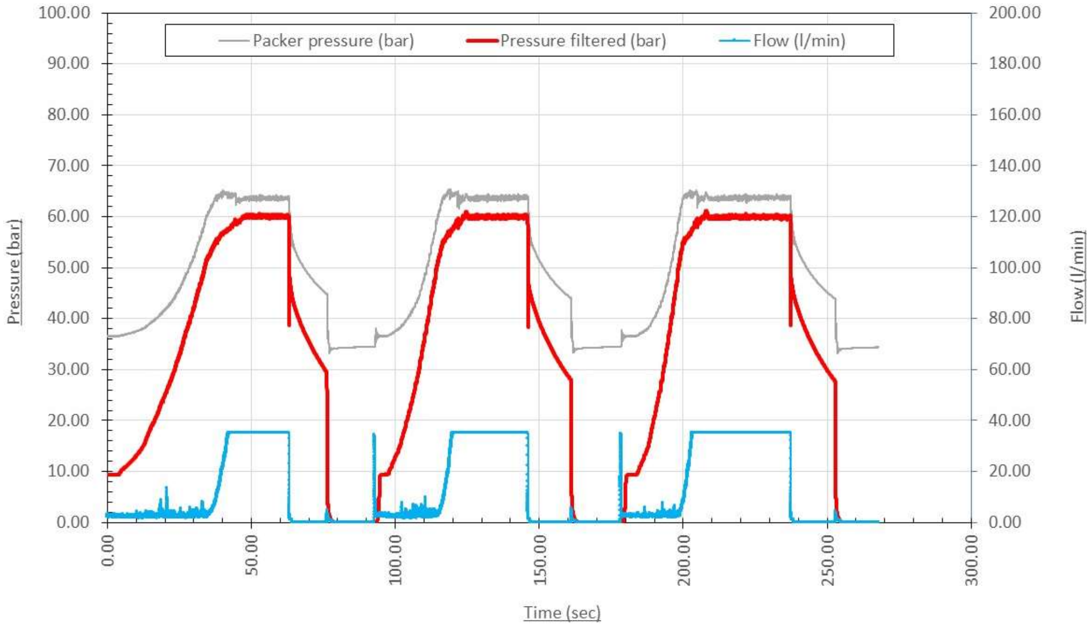

Fig. 3 Shut-in test for pressure level "50 bar".

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 *dPw/dt* vs. *Pw* (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.

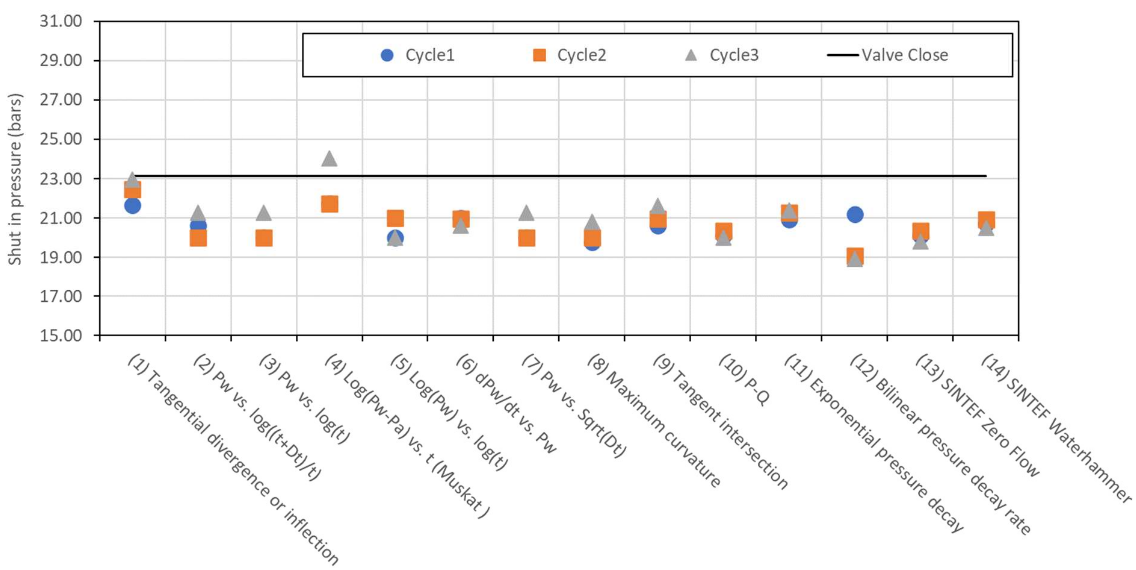

Fig. 4 Results of shut-in pressure calculation in "25 bar" tests, in comparison to the closing pressure of the spring valve.

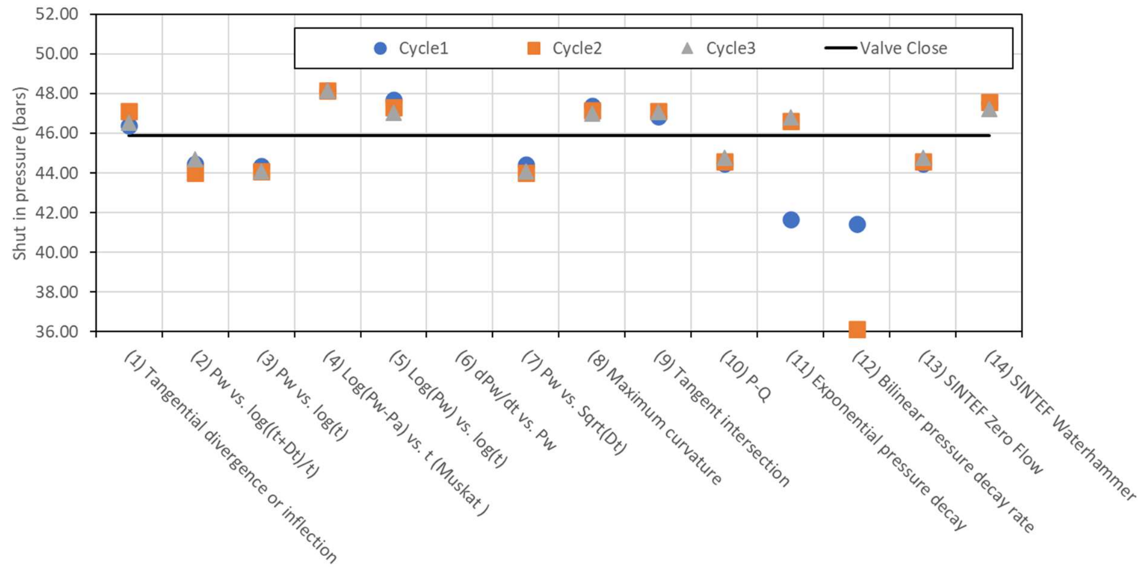

Fig. 5 Results of shut-in pressure calculation in "50 bar" tests, in comparison to the closing pressure of the spring valve.

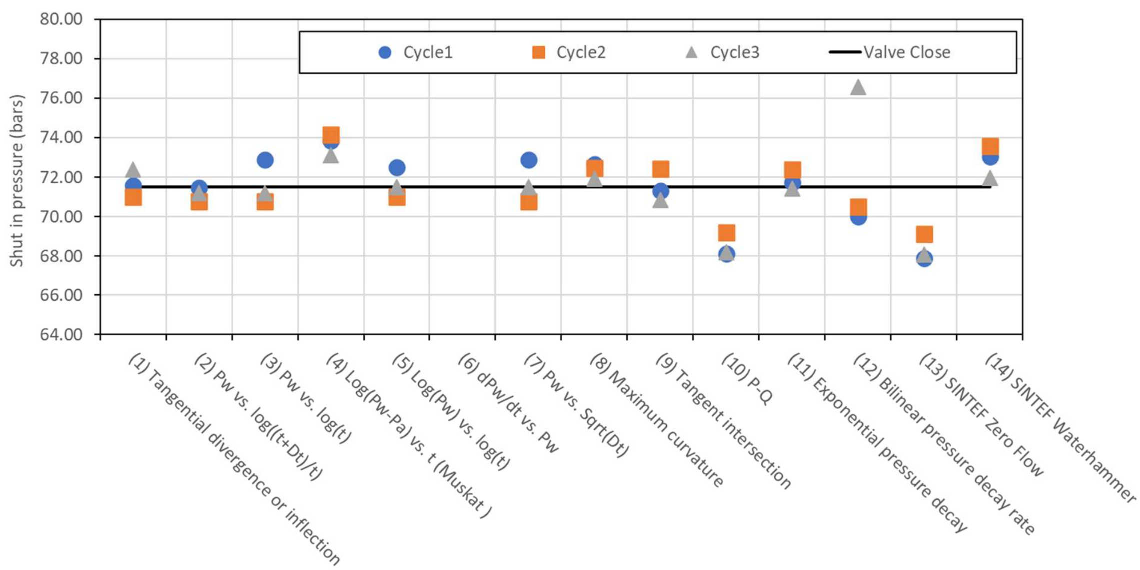

Fig. 6 Results of shut-in pressure calculation in "75 bar" tests, in comparison to the closing pressure of the spring valve.

5 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 discuss the findings from laboratory and in-situ tests. It seems that shut-in pressure defined by the *water hammer* method is corresponding to ISIP, and shut-in pressure defined by the *zero flow* method is corresponding to closure pressure.

From our practical experience, it is important to note that:

- 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).

The results of shut-in pressure determination based on these two methods were compared with 12 other existing 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. It is however that the two new methods require high frequency simultaneously data sampling up to 50 Hz and a proper data filtering.

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