Development of an algorithm to detect hydraulic jacking in high pressure rock mass grouting and introduction of the PF index

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Abstract

Pre-excavation rock mass grouting is a common procedure for reducing water ingress into tunnels during construction in Norwegian tunnelling. The level of grouting pressure is a disputed subject and the knowledge of how the rock mass responds to the high pressure and how this inflicts on the grouting results is sparse and little investigated. For this reason, it is of interest to use data from high pressure grouting performed in Norwegian projects to investigate these matters. This paper presents the development of a method for identifying hydraulic jacking during rock mass grouting and the making of an algorithm to perform computerized detection of hydraulic jacking in grouting logs. The algorithm is the base for a larger study, where screening for hydraulic jacking is performed in over hundred grouting rounds, distributed on several Norwegian tunnels excavated in rock mass. The relation between grout flow and grouting pressure has shown to be vital for the understanding of the grouting progress and events occurring during the grouting. Interpretation of pressure and flow as two separate variables, which are affected by aliasing, caused by low and irregular sampling frequency is a challenging task, and it was found to be helpful to create a parameter to represent this relationship, named the PF index (Pressure Flow index). This parameter has also shown to be useful in other applications such as monitoring the grouting progress on site.

Keywords: rock mass grouting, hydraulic jacking

1. Introduction

Pre-excavation rock mass grouting is a common procedure for reducing water ingress into tunnels during construction in Norwegian tunnelling. The methodology used in Norway is developed through many years of practical experience in underground excavations such as road and railroad tunnels in both urban and rural areas, subsea tunnels and hydroelectric power development. As a result of the prior experience and a research project called "Tunnels for the citizens" in the early 2000s, the grouting pressure used is high compared to e.g. US and Swedish practice. Common grouting pressures in Norwegian tunnelling projects are 60-80 bar, largely depending on the overburden and geology. One of the most important motivations for using high grouting pressure, is to ensure penetration of grout into fine fractures. The knowledge of how the rock mass respond to the high pressure and how this inflicts on the grouting results is sparse and little investigated, at the same time the pressure is a disputed subject in Norway and even more in many other countries.

The most controversial effect from grouting with high pressure is hydraulic jacking of fractures existing in the rock mass. Some of the discussed issues are; at which pressure can hydraulic jacking be expected, what are the risks connected to this event, how does it inflict on the sealing effect of the tunnel, how does it affect the usage of time and cost for the tunnelling project? To investigate these matters it is if interest to identify occurrences of hydraulic jacking during rock mass grouting and collect relevant information

related to these events. Data from pre-excavation rock mass grouting performed in Norwegian projects are well suited for this type of study as high grouting pressure is common procedure.

Initially in this study grouting pressure and flow during grouting were examined by visual inspection of graphs from grouting logs. The grouting logs were retrieved from contractors, after the grouting work was finished. The sites were Norwegian road and railroad tunnels excavated with drill and blast in hard rock mass, such as granitic gneiss. The method of grouting was high pressure pre-excavation grouting with grouting pressures up to 80 bar, both systematic grouting with overlapping rounds and grouting on demand. The grout was cement based and made from Portland clinker, additive was superplasticiser. Silica was added if industrial cement was used.

The purpose of this initial work was to learn about typical grouting behaviour, find evidence of hydraulic jacking and learn how the operators pursued the criteria given in the contract. During this work, it was learned that the grouting progress of each hole differs greatly, the operator's technique has great variability and that hydraulic jacking is a very common occurrence during grouting in Norwegian tunnelling projects. To achieve a correct identification of hydraulic jacking in the available data, it is essential to find a reliable characterisation for hydraulic jacking. By defining boundary conditions for hydraulic jacking in the data, it would be possible to interpret larger datasets and ensure the reproducibility of the results.

This paper presents the development of a method for identification of hydraulic jacking during rock mass grouting and the making of an algorithm to perform computerized detection of hydraulic jacking in grouting logs. The algorithm is the base for a larger study consisting of screening for hydraulic jacking in data obtained from over hundred grouting rounds distributed on several Norwegian tunnels excavated in rock mass. In future publications, the results generated from the algorithm will be compared to geological parameters, theoretical assumptions on when hydraulic jacking will occur, type of grout, grout consumption and time usage.

2. Hydraulic jacking

Hydraulic jacking occurs when the pressure inside the fracture is higher than the normal pressure acting on the fracture. This force makes the fracture open, which means that the aperture of the fracture is increasing. Gothäll and Stille (2009) suggests that this process is evolving through three different regimes. The first regime is the low pressure regime where the major part of the load is carried by the contact asperities in the fracture, the second regime is the critical regime where the pressure in the asperities is equal to the pressure of the fluid/grout. The final regime is the post-critical regime, where the grout pressure exceeds the normal pressure and the asperities are no longer in contact. All three regimes may be present at the same time during grouting, but in different parts of the fracture. During unloading of the asperities in the transition between the low pressure regime and the critical regime, the dilation of the fracture will be of the same scale as the decrease in elastic deformation of the asperities. The increase in the fracture aperture during this process is estimated to be five percent or less, if the fracture walls are reasonably matched. This aperture increase is relatively small and of no practical importance for grouting, according to Gothäll and Stille (2009). In the post-critical regime, the increase in aperture is significant and with practical importance for the grouting. A significant increase in aperture would lead to a change in the flow pattern of the cement, which could be visible in the flow and pressure data recorded at the grouting rig.

3. Detecting hydraulic jacking from pressure and grouting logs

There are not many publications which discuss detailed and quantified definition of hydraulic jacking during rock mass grouting regarding interpretation of real data, but some authors discuss how hydraulic jacking can be discovered by using the logged data.

Lombardi and Deere (1993) suggest how hydraulic fracturing or jacking can be detected by looking at the ratio between the flow and the pressure, by dividing flow (Q) on pressure (P), as illustrated in Fig. 1. The curve in graph (d), showing the Q/P ratio over time, decrease as the resistance in the hole is increasing. The sharp peak in the graph is referred to as hydraulic fracturing, or jacking. Just before the pronounced peak in the Q/P ratio, the pressure is dropping (a) and the flow is increasing (b).
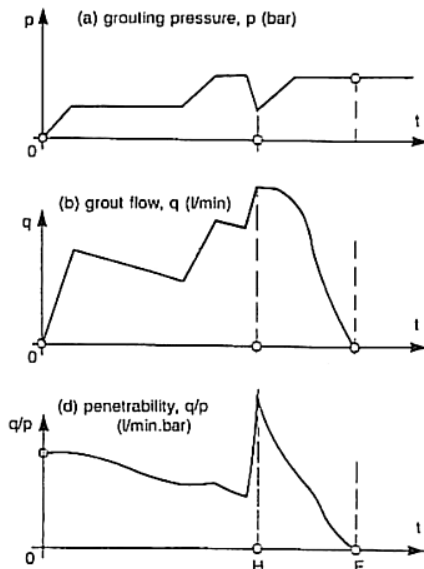

Fig. 1. a) Grouting pressure during hydraulic jacking/fracturing (H), b) flow during H and d) Q/P ratio during H (Lombardi and Deere, 1993).
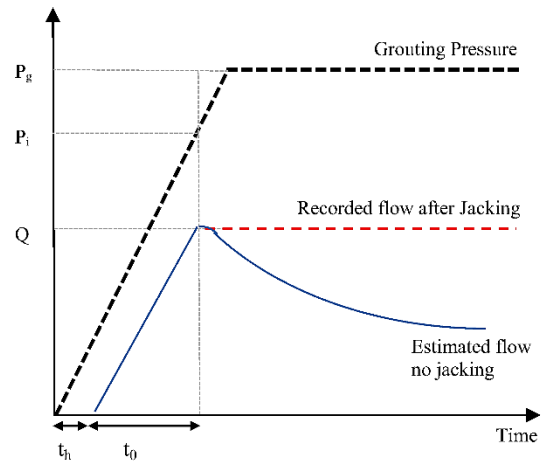
Fig. 2. Recorded flow and estimated flow using the RTGC method (Rafi, 2014)

Rafi (2014) presented Fig. 2, as an example on how one can distinguish hydraulic jacking of a rock fracture in a grouting log. The figure is based on the Real Time Grouting Control method (RTGC), where the grouting work is evaluated with back analysis and it is possible to estimate the expected flow (Stille, 2015). This back calculation requires knowledge of the yield value and the viscosity of the grout. In this case the predicted flow is estimated to decrease while the pressure is stabilizing, as expected when cement based grout is flowing as a 1D (channel) or 2D (disc) flow in a fracture with a constant aperture. The recorded flow is deviating from the estimated flow behaviour and is steady, not decreasing as expected. If the recorded flow behaviour is deviating from the predicted flow it is either due to wrong assumption of the dimensionality, the aperture size or, hydraulic jacking of the fracture (Rafi, 2014).

Fig. 3 shows a graph of the recorded flow and pressure from a real grouting project in Laos presented by Rafi and Stille (2014). The predicted grout flow is estimated by using the RTGC-method. The onset of the jacking event is when the recorded flow is deviating from the predicted flow, which in this case is when the pressure is stabilizing, at a steady flow rate. There might be other explanations for this type of behaviour of the flow and pressure, as there are several plausible reasons for wrong assumption of the dimensionality and change in aperture size in a fracture, which could represent a pressure and flow

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behaviour similar to events representing hydraulic jacking or fracturing. This will be discussed further in section 4.2.
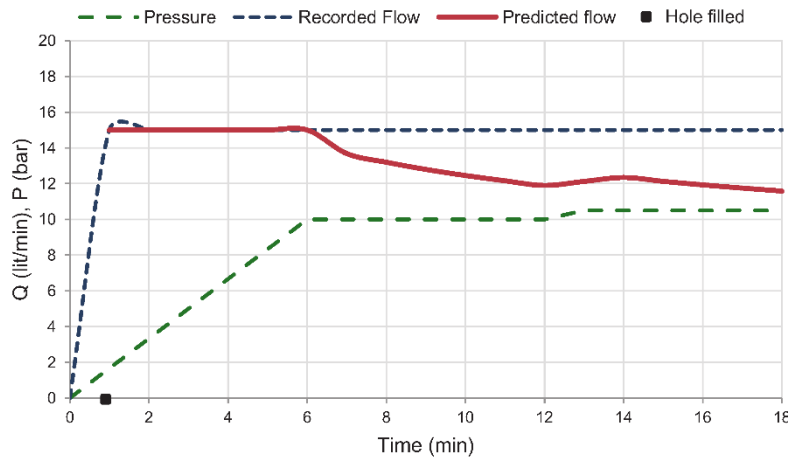

Fig. 3. Recorded flow and estimated flow using the RTGC method on real data (Rafi and Stille, 2014)

Warner (2004) is putting emphasis on the pressure drop at a constant flowrate as a symptom of hydraulic jacking, but also list numerous events that could cause a pressure drop at a constant flow rate:

1. hydraulic fracturing
2. grout loss into a concealed pipe or other substructure
3. outward displacement of a downslope or retaining wall
4. grout entering much larger fractures or voids
5. grout encountering a softer or more permeable formation
6. thinning the grout or other rheological change that increases mobility
7. leakage of grout and pump malfunction

Warner (2004) also stated that reduction in the pressure increase during the pressure build-up at a constant flow rate, could indicate a significant event in the grouting.

The technique of hydraulic fracturing for estimating the minimum in-situ stress component in rock mass, is also a potential source for learning about the behaviour of flow and pressure in hydraulic jacking during rock mass grouting. The method is performed by isolating a section of a borehole by pressurizing two inflatable packers. The section is placed in intact rock with no prior fractures. Water is pumped into the sealed off section until a fracture is generated, known as hydraulic fracturing. The procedure is repeated at least two times, resulting in a reopening of the generated fracture, known as hydraulic jacking. The procedure is described in detail in ASTM International (2004). The method is well established and a common method for stress measurements in rock mass in Norway.

4. Method

4.1. Discussion of applicable methods for defining hydraulic jacking in grouting logs

The first process in this research was visual inspection of graphs from grouting logs and literature study, followed by trial and error approach with data from finished grouting projects with the use of theories and material published by Lombardi and Deere (1993), Stille (2015), Warner (2004) and ASTM International

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(2004), described above.

The RTGC method was not found to be a suitable method for detecting hydraulic jacking, because the rheology of the cement in the available data was unknown and the method is primarily designed for predicting the spread of grout over time. It was concluded that this method could have potential for detecting hydraulic jacking in the future, with continuous measurements of the rheology of the grout during the grouting process.

The Q/P ratio presented by Lombardi and Deere (1993), was a promising approach, but did not work well with Norwegian data because of the use of high pressure. If the flow is small, and the grouting pressure is high, a significant drop in the pressure would not result in a significant change in the Q/P ratio, which was often the case in the available data.

The behaviour of flow and pressure presented by hydraulic fracturing for in-situ stress testing was also found not to be directly applicable for this study. Table 1 lists some vital differences between hydraulic fracturing for in-situ stress testing and pre-excavation grouting. In practical sense, this means that during the hydraulic fracturing a new fracture is generated and for each time the newly generated fracture is jacked, the fracture is expanding. This means that the water cannot penetrate past the fracture tip, while in rock mass grouting, a fracture of unknown extent is already existing. In most cases the fracture is filled with water before the grouting takes place, also the jacked area might occur in a part of the fracture where the grout front already has passed. For this reason, when jacking occurs the response from the flow and pressure would be of different scale and it is reasonable to believe that the change in pressure and flow would be more significant in grouting. Also, the response during hydraulic jacking would be different with a Newtonian and a Non-Newtonian fluid.

Table 1 Differences between hydraulic fracturing (HF) for stress measurement and hydraulic jacking (HJ) of fractures in rock mass grouting

	Parameter	HF	HJ
1	Fluid	Water (Newtonian fluid)	Cement based grout (non-Newtonian fluid)
2	Hole section	1 meter	13-27 metres
3	Fractures	No pre-existing	Pre-existing
4	No. of fractures	1 generated	Unknown
5	State of fractures	Fracture propagates during reopening cycles. No fracture infilling.	Unknown extent of fractures, and apertures may vary greatly. Might have fracture infilling.
6	Orientation of fractures	Generated perpendicular to direction of least in-situ stress	Random orientation
7	Sampling interval	< 1 sec	Approximately every 10th sec.

The general understanding derived from the theory presented from Lombardi and Deere (1993), Stille (2015), Warner (2004) and ASTM International (2004) is that hydraulic jacking can be detected by the following pressure and flow behaviour:

- sudden decrease in pressure while flow is stable
- sudden increase in flow while pressure is stable
- both decrease in pressure and increase in flow
- steady flow and pressure, after a period of pressure increase

4.2. Different events with similar responses of pressure and flow behaviour

Is the suggested pressure and flow behaviour the signature for hydraulic jacking, or could there be other events during the grouting that could exhibit the same behaviour? Both Rafi (2014) and Warner (2004) states that this is the case. Therefore, it was important to distinguish these events from the data and remove them, to ensure a representative selection of hydraulic jacking events for further analysis. To obtain an understanding of the behaviour of grout flowing through sections of changing geometry, a simple numerical model was made to illustrate the behaviour of a Bingham fluid trough changing geometries, Fig. 4.
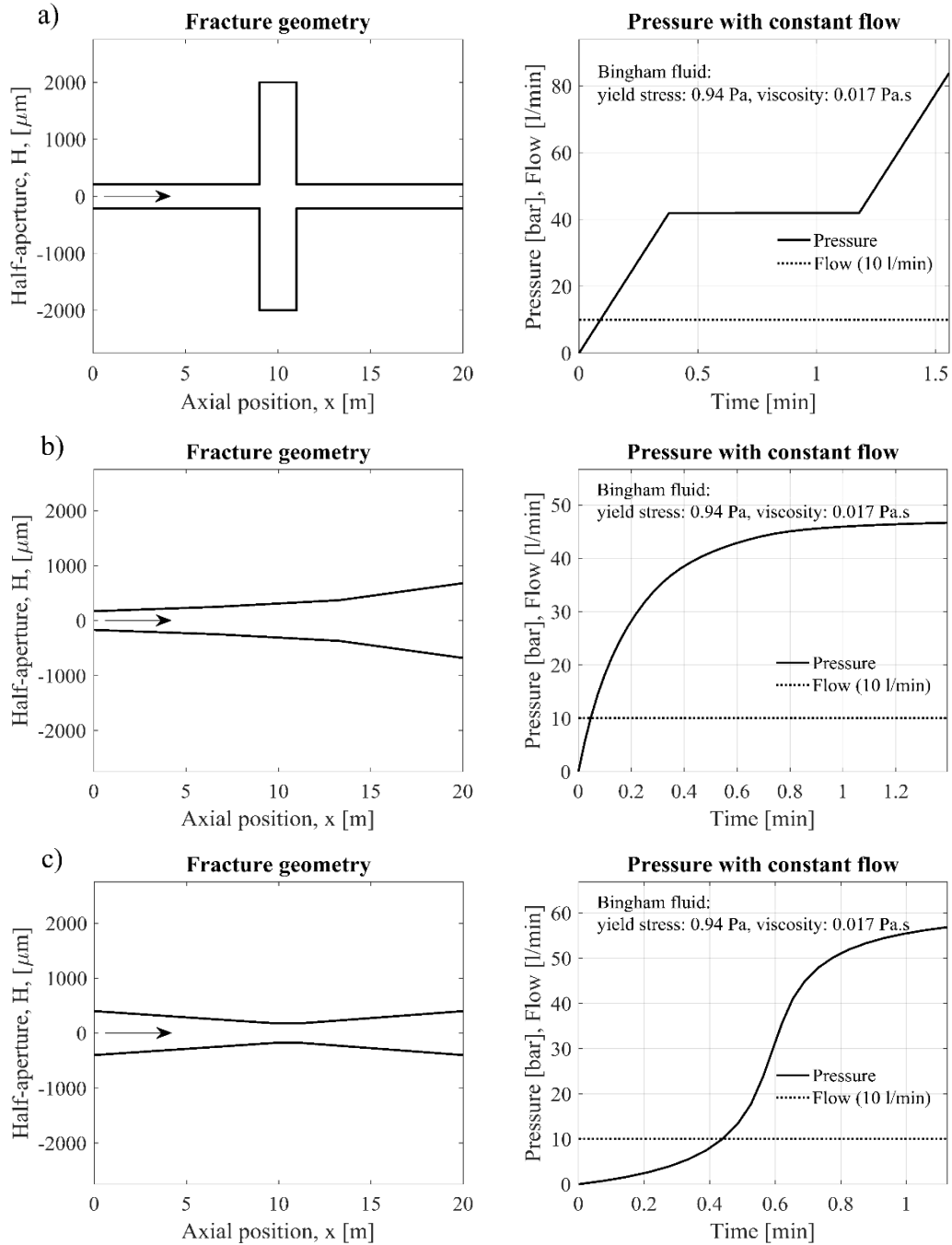
Fig. 4. Numerical model a) grout flowing in a channel, encountering a void and the accompanying flow and pressure behaviour. Model b) grout flowing in a channel with increasing aperture. Model c) grout flowing through a channel with a constriction.

The simulation was made by designing a 2D numerical model of a Bingham fluid flowing in a 1 metre wide channel between two surfaces with changing aperture, the method for modelling is derived from Morris et al. (2015). The yield stress and the viscosity of the Bingham fluid was respectively, 0.94 Pa and 0.017 Pa.s. These values were derived from Eriksson et al. (2004), and is representing ordinary Portland cement, milled down to a d_{95} of 30 μm, mixed in a field mixer with a w/c ratio of 0.8 and 1% superplasticizer. All simulations have a channel length of 20 metres, with a constant flow of 10 l/min.

Fig. 4 shows the results from the simulation of the three different fracture geometries. In model a) the aperture of the channel is 420 µm. In a section of 2 metres the aperture is increased to 4 mm, representing a void in the channel. The simulation shows a linear increase in pressure before the grout is entering the void. This pressure behaviour is as expected because of the increase in total friction in the flow path. After the grout front enters the void there is no significant increase in friction, before the void is filled with grout, which means that the pressure is almost constant. As the grout front is forced through the last section with smaller aperture, new friction is added to the system and the pressure is increasing. This means if grout is entering a void, or an open space, and the fracture geometry before the open space remains unchanged, and the rheology of the grout is unchanged, the pressure will not decrease at a constant flow rate, as suggested by Warner (2004), point 2, 4 and 5 in section 3. Also, this simulation indicates that stabilizing pressure after a pressure increase at a constant flow, does not necessarily mean hydraulic jacking.

In model b) the channel has an increasing aperture, from 340 µm to 1360 µm. The simulation shows a rapidly increase in pressure, as the total friction in the channel is increasing rapid in the narrow area. As the aperture in the channel increases, less friction per length of channel is added and the increase in pressure is reduced significantly. This illustrates that a grouting log with constant flow and a pressure increase followed by a relative stable pressure could indicate an increase in fracture aperture, increase in width of the fracture, grout entering a void/open space, or intersecting another fracture.

In model c) the simulation is showing a channel with a constriction. Initially the aperture is decreasing from 400 µm to 180 µm, followed by an increase to 400 µm. The simulation shows a relatively low increase in pressure followed by a rapid increase in pressure as the channel aperture is decreasing. When the grout enters the section with the increasing aperture, the increase in friction per length of channel is significantly reduced, and the increase in pressure is also significantly reduced.

In other words, as the front of the grout moves through the fracture system, it is accumulating friction. As long as the source of the friction in the pathway remains unchanged and the flow is constant or increasing and the rheology of the grout is unchanged or getting thicker, these simulations indicate that it is not possible to see a fall in pressure. An exception would be occurrences at the grouting rig. Grout eroding the fracture or bursting through joint fillings blocking the flow path, might result in a reduction in pressure under a constant, or increasing flow. Hydraulic jacking, where the fracture aperture is increasing, or hydraulic fracturing, where a new fracture is generating a new pathway for the grout, could also exhibit this flow and pressure behaviour.

It was concluded that the following events could exhibit steady flow and pressure, after a period of pressure increase:

- larger aperture further out in the fracture
- the grout is first flowing in a channel and then starts radial flow when the grout reaches a more open area (from 1D flow to 2D flow).
- the grout has reached an intersection with another fracture
- the grout has reached a void, a free surface, or a neighbouring drill hole
- erosion of material in the fracture
- grout bursting through joint fillings blocking the flow path

- changing rheology of the grout
- grout set in to motion after a stoppage or rapid increase of flow
- hydraulic jacking

In the grouting logs, it is not possible to distinguish between most of these numerous events because of the unknown geometry of the fracture systems and no continuous verification of the grout rheology during the grouting. It was therefore decided to exclude steady flow and pressure, after a period of pressure increase as an indicator for hydraulic jacking in this study.

It was concluded that the following common events could exhibit a decreasing or stable pressure behaviour while the flow is increasing, alternatively increasing or stable flow while the pressure is decreasing:

1. hydraulic fracturing
2. grout set in to motion after a stoppage or rapid increase of flow
3. sudden washout of fine material that caused constrictions in the fracture
4. the grout bursting through joint fillings blocking the flow path
5. increase of flow while the grout is filling an open void
6. hydraulic jacking

Hydraulic fracturing of intact crystalline rock would require significantly higher pressure than 80 bar. In Norwegian tunnelling projects, grouting of holes that do not take grout is terminated because of the risk of ejection of the packer and the attached grouting rod. Therefore, it is not likely that hydraulic fracturing is occurring during grouting in the projects presented in this study. To avoid recording events caused by rapid increase in flow by the operator, or when grout was set in motion after stoppage, as described in point 2 above, it was decided that sudden significant increase in flow, or the first 40 seconds of grouting after stoppage should not be screened for hydraulic jacking. It was also decided that the first 90 seconds after the grouting has started should not be screened for hydraulic jacking, because of hole filling and transition for the grout to start filling fractures. The detailed specifications regarding these decisions can be studied in Appendix A. Originally the screening was set to begin when pumped volume was larger than hole volume, but this approach did not fit the real data. The reason for this is probably that many holes are filled with water or grout from linked holes before the grouting starts.

The specific details regarding flow and the length of the time periods mentioned, were decided after a careful study of grouting behavior in different projects, grouting rigs and operators. These restrictions will eliminate events with hydraulic jacking occurring during rapid changes on the grouting rig, but because of the uncertainties it would bring to the results it was chosen to apply these restrictions.

The research so far has not revealed a method to differentiate sudden washout of material that have caused constrictions and blockades in the flow path. It is assumed that such events occur at lower pressures than hydraulic jacking. Further work is planned to analyse the correlation between site parameters and events occurring at low pressures, and new knowledge is expected to be obtained.

During the trials with real data it was also found issues regarding the relation between flow and pressure when grouting in very open fracture systems. When the fracture system is filled with fluid (water/grout) the interaction between flow and pressure is very respondent, which mean that if the flow is increased, the pressure is increasing as a response. If the grout is filling an open void/fracture, it seems like the pressure

does not respond as pronounced. This hypothesis is partly supported by the numerical model shown in Fig. 4, numerical model a). This can result in false positive jacking events in open fracture systems with a high grout take. Since it is difficult to achieve high pressure under such conditions, these false recorded hydraulic jacking events will be occurring at low pressures. This is another reason why it is important to examine the results for hydraulic jacking recorded at low pressures more thoroughly. In this study, it is chosen to leave out events occurring when the value of pressure, given in bar, is equal to or lower than the value of the flow, given in l/min, because it indicates high flow with little response in pressure increase. The criterion is valid only when the event is starting, not during the event. This measure does not solve the issue, but reduce the extent of the issue.

4.3. Interpretation of real data

A major challenge during the interpretation of data from the grouting rigs was, low sampling rate in combination with oscillations in pressure and flow caused by the piston/plunger pump. The sampling rate is approximately every 10th second on some grouting rigs, whilst on other grouting rigs the sampling rate is more irregular and approximately every 17th second. Both infrequent and irregular sampling causes aliasing, and the behaviour of the flow and pressure between each sampling is unknown. Handling data with aliasing is challenging and can lead to misinterpretation; data from grouting rigs with a sampling frequency lower than every 10th second are therefore eliminated from the study.

Another important issue in this analysis is how representative the pressure measured at the grouting rig is for the pressure in the grouting hole. Tests performed have shown that pressure measured on the grouting rigs is slightly lower, but close to the pressure inside the grouting hole (Tunbridge et al., 2014). The pressure loss from the grouting rig to the hole is small, this also includes the oscillation caused by the piston or plunger on the grouting pump, see Fig. 5. In this case the sampling rate on the pressure logger in the hole is once every second, while the sampling rate on the grouting rig is once every 10th second. The pressure curve indicated by the extrapolation between samplings on the rig every 10th second is very similar in shape to the pressure curve indicated by the extrapolation between samplings in the hole every second. This result indicates little aliasing in the data, as long as the pump cycle is 20 seconds or longer while the sampling rate is every 10th second (Nyquist criterion).
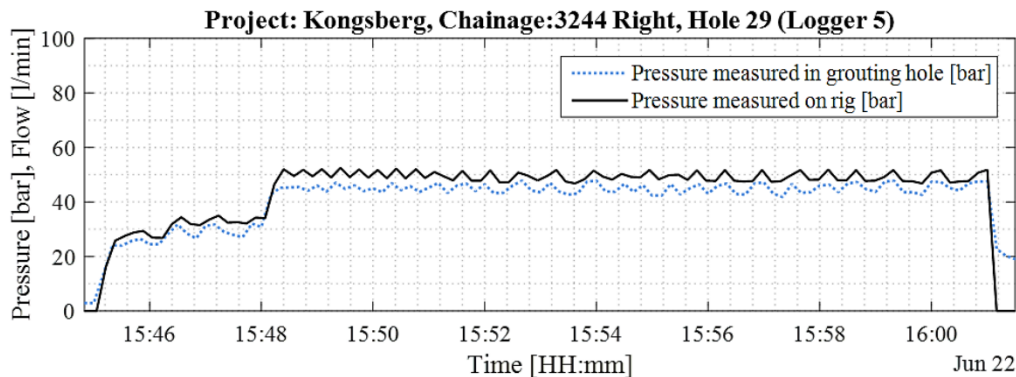

Fig. 5. Grouting pressure measured at the rig every 10th second and grouting pressure measured in the hole every second (Strømsvik and Grøv, 2017).

The oscillation in pressure in combination with low sampling frequency, is considered as a negative factor in this study, but it is important to emphasise that the oscillating pressure could give a positive effect on the grouting process with regard to penetration of cement into small fractures (Ghafar et al., 2016).

4.4. Development of the PF index

Interpretation of pressure and flow as two separate variables, which are affected by oscillations by the piston/plunger pump and low sampling frequency, turned out to be a challenging task. It was soon discovered that it would be useful to find a parameter that could represent the relation between flow and pressure. Such a parameter could illustrate the grouting process and emphasize changes in the relationship between pressure and flow, that could indicate the occurrence of significant events, e.g. hydraulic jacking and be useful when defining boundary conditions for detecting hydraulic jacking in the data.

Different methods for illustrating the relation between pressure and flow were investigated. The first approach was using the Q/P ratio presented by Lombardi and Deere (1993). Since this was not found to be an adequate method for Norwegian projects, new alternatives were investigated. It was found that by simply subtracting the pressure from the flow the pressure build-up is represented in a distinct way, as well as the general relationship between the volumetric flow and the pressure. To create a dimensionless value with a practical scale, some adjustments were made to the formula. Addition of 90, creates a positive value and multiplication with 0.9 adjusts the range of the scale. This value is hereby called the PF index (Pressure Flow index), Formula 1. The PF index was first introduced as the QP index in Strømsvik and Grøv (2017), but is slightly modified afterwards to make the index dimensionless.

$$PF\ index = 0.9\ {}^{min}/_l * Q_v - \frac{0.9 * P}{1\ bar} + 81 \qquad (1)$$

Where Q_v is flow given in l/min and P is the grouting pressure measured at the grouting rig given in bar.
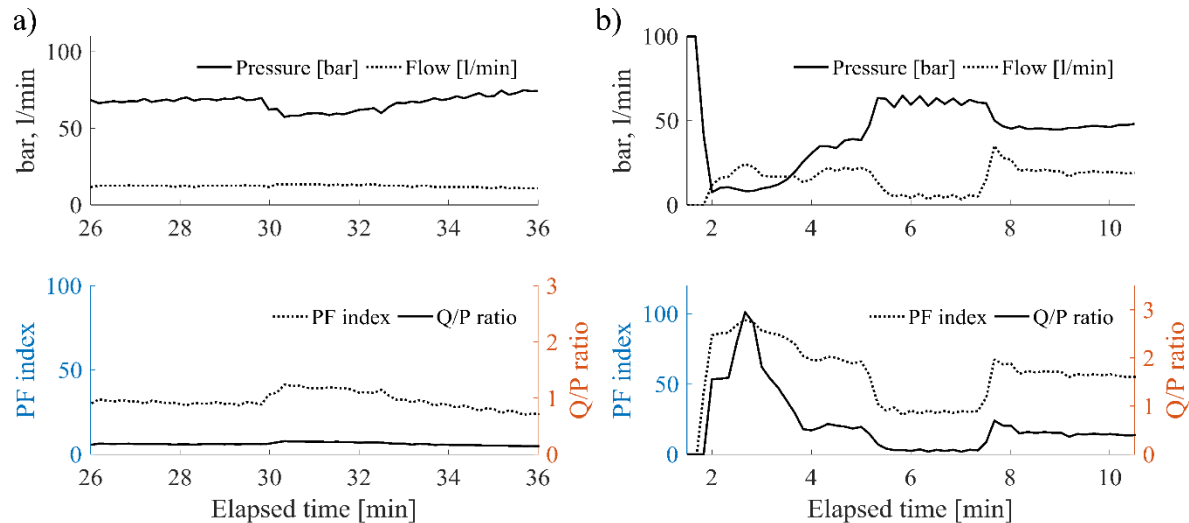

Fig. 6. a) and b) pressure and flow over time with the accompanying PF index and Q/P ratio shown beneath.

Fig. 6, examples a) and b) show comparisons of the Q/P ratio and the PF index. In example a) the flow is stable at approximately 15 l/min, 30 minutes after the grouting has started there is a pressure drop, with a slight increase in flow, which can indicate the occurrence of a hydraulic jacking. This event is accompanied by a significant increase in the PF index, but the Q/P ratio does not give any significant indication of this event. In example b) the event occurring after 7 minutes and 30 seconds of grouting indicate hydraulic jacking. The event is more distinct than in example a) and both PF index and Q/P ratio show a significant increase during this event, but the PF index is more pronounced compared to the

maximum and minimum values of the PF index and Q/P ratio. These examples illustrate why the PF index is the preferred choice for recognising hydraulic jacking.

To be able to use the PF index as a tool for computerized interpretation of hydraulic jacking on data logs from the Norwegian projects it was necessary to perform further adjustments by filtering the data, this process will be described in section 4.4.2., 4.4.3.

4.4.1. Interpretation of flow

On the grouting rigs the flow is measured by a flowmeter, and in addition the pumped volume is often continuously measured. This means that the volumetric flow is measured in two different ways. The measurement by the flowmeter is greatly dependent on the timing of the sampling in the pumping cycle, consequently if this measurement is used to back calculate the pumped volume, it would give incorrect results. If the pumped volume is used to estimate the volumetric flow over time, the flow is not effected by the pump strokes to the same extent, but directly related to the actual pumped volume. After a trial with both parameters it was chosen to use the measurement from the pumped volume to calculate the value for volumetric flow (Q_v), when calculating the PF index. The measurement performed by the flow meter (Q) is also an important parameter in the detailed analysis in the algorithm. The specific details can be found in Appendix A, where a detailed flow chart of the algorithm is presented.

4.4.2. Filtering pressure data

In some of the grouting logs, sudden large pressure drops occurred occasionally, followed by a similar pressure increase in the next sampling whilst the pressure and flow were in general steady, see Fig. 7 a). The reason for these occurrences are not known but these events are not related to hydraulic jacking or fracturing, therefore a moving median with a span of three was applied to the logged pressure to remove these events from the data. The large sudden drops in pressure have significant effect on the PF index, as seen in Fig. 7 b), where the pressure drop has influenced the PF index over a larger time span. This is due to a moving average filter applied on the PF index, described in the next section. In some cases, this pressure drop could wrongfully be interpreted as hydraulic jacking and this is the reason for using the moving median filter on the pressure log.

4.4.3. Filtering of the PF index

The purpose of the PF index is to present an overall trend of the grouting progress. The oscillation in pressure and flow caused by the pump is considered to be noise in the data, and thus the PF index can be smoothed. This does not mean that the oscillations are removed from the full analysis, but only in the PF index. A double moving average filter with a span of five, has shown to be effective in removing the oscillations, but preserving the general trend of the grouting behaviour. The span of five is adapted to data where sampling is approximately every 10ᵗʰ second, and must be reassessed with other sampling intervals. By using such filtering, one must be aware that a sudden event will affect the neighbouring samplings as shown in Fig. 7 b). On the three samplings closest to a sudden decrease of the flow by the operator, the moving average filters should not be applied directly, but be applied separately. Otherwise, abrupt changes in the pumping will be smeared out by the filter, and might lead to erroneous interpretation of hydraulic jacking.
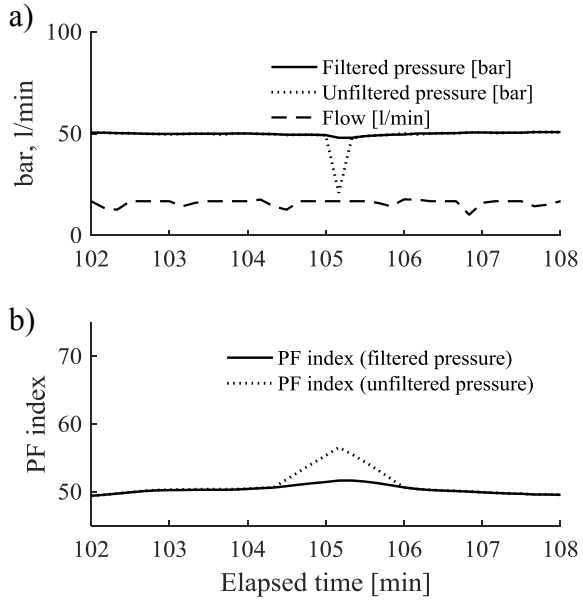
Fig. 7. a) Filtered pressure and unfiltered pressure, b) PF index estimated with filtered and unfiltered pressure.

4.5. Creating the algorithm

The PF index in combination with logged pressure, flow and time was further used to create an algorithm which can indicate the onset of events plausible to be hydraulic jacking. The algorithm was developed and tuned through analysis of a great number of grouting rounds from varying geology, overburden, w/c ratios, grouting rigs, operators and projects, to ensure that the algorithm would work correctly for the different tunnelling conditions. The boundary conditions for what is considered as a hydraulic jacking or not, is based on the literature study, study of hydraulic fracturing tests, the simulations with the 2D numerical model and study of grouting logs from pre-excavation grouting in rock mass in Norway.

5. Results

5.1. Algorithm to detect events in grouting rig data in rock mass grouting

The main attribute of the algorithm is that the PF index should increase by a given value within a limited timeframe, at the same time as the pressure is stable or reduced while the flow is stable or increasing. In addition, the algorithm can identify and exclude the following scenarios in the grouting behaviour:

- start of grouting, or restart after temporary stoppage
- rapid reduction of flow by operator (also decrease in pressure)
- rapid increase of flow by the operator (also increase in pressure)
- repeated rhythmic pressure drops caused at the pump by the pumping cycle

Fig. 8, shows a flow chart illustrating the structure of the algorithm created for detecting events indicating hydraulic jacking. A detailed flow chart of the algorithm is presented in Appendix A.
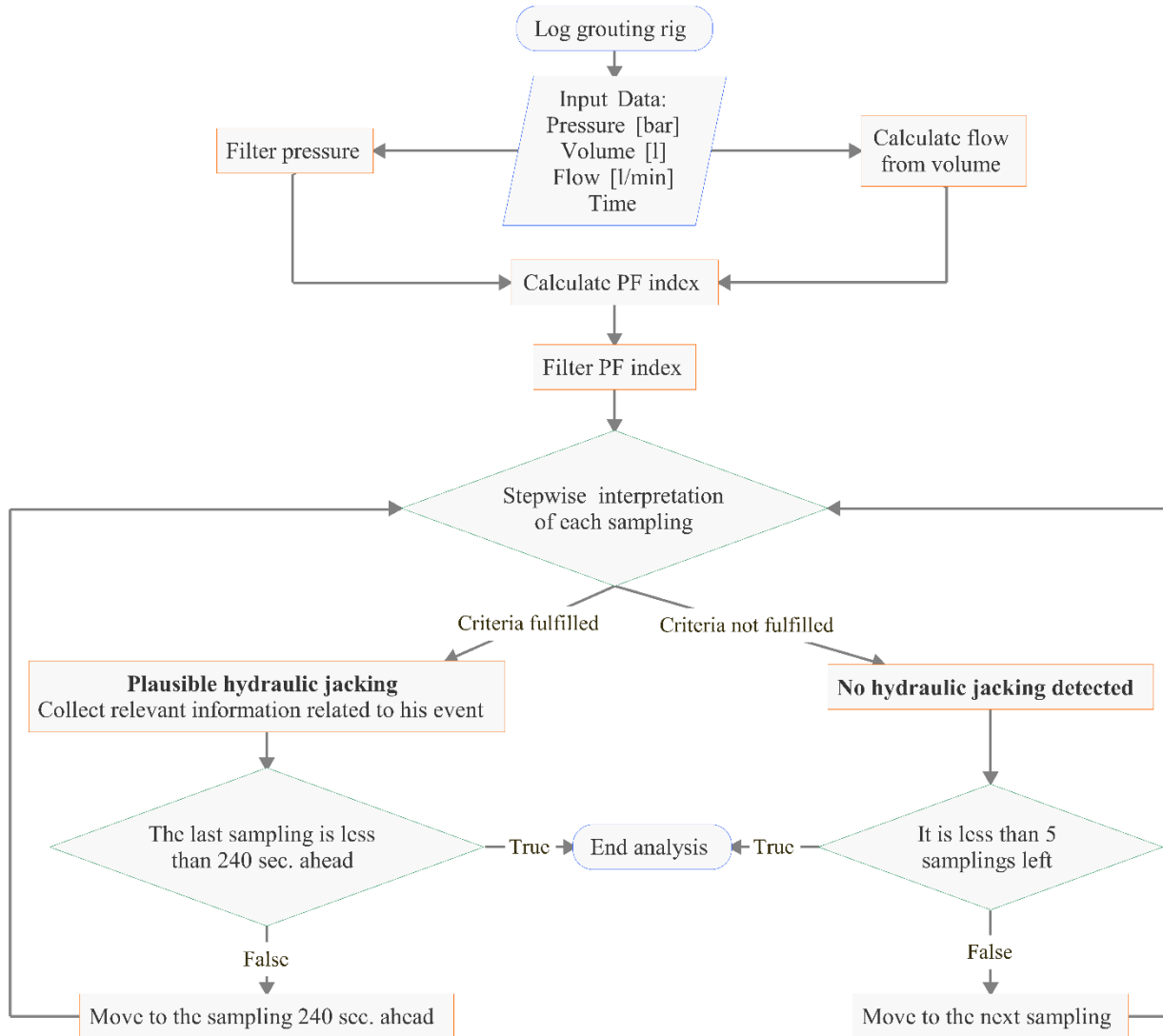
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Fig. 8. Flow chart showing the structure of the algorithm created to detect hydraulic jacking in data logs from grouting rigs.

When the algorithm has located potential jacking, information related to the event is gathered, such as total volume grouted, time, pressure, integral of pressure, etc. This information can be compared to the data from the site, such as grout type/properties, overburden, rock mass quality, etc.

Fig. 9, examples a) and b) show a graphic view of two plausible events where the onset of hydraulic jacking is identified by the algorithm. In example a) there is a pressure drop with a relative constant flow and in example b) there is both increase in flow and decrease in pressure where the algorithm indicates the plausible jacking. The case shown in b) is slightly more complicated to interpret because of several
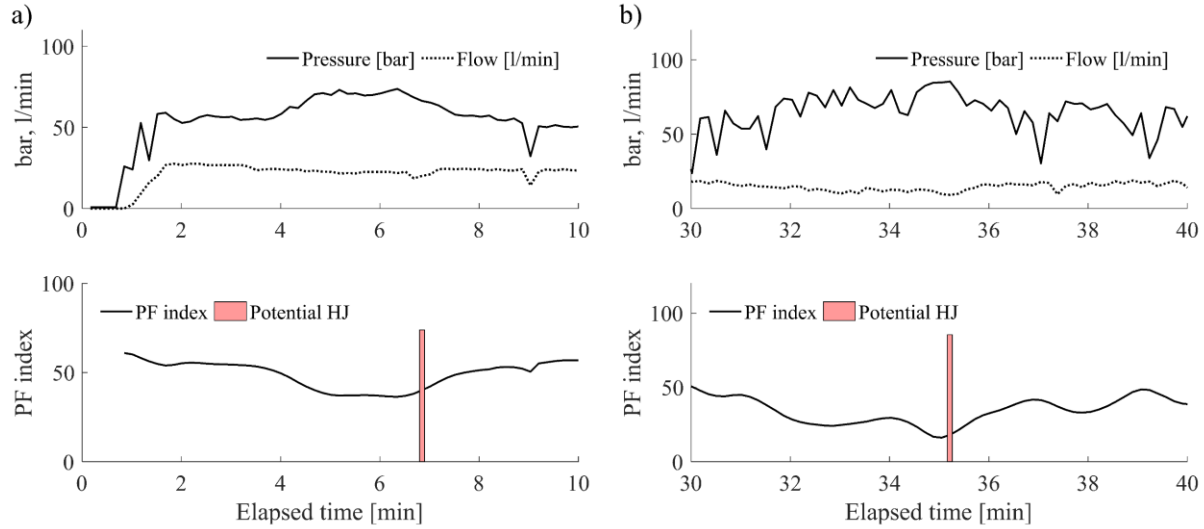
Fig. 9. a) and b) pressure and flow over time with the accompanying PF index beneath. The bar on the PF index is marking the onset of hydraulic jacking (HJ).

events with an increase in the PF index and high fluctuations in the pressure, but the boundary conditions given for hydraulic jacking appear to be set at an appropriate level, as the algorithm identifies the most likely jacking event.

5.2. Other uses of the PF index

The PF index was created as a tool in computerized screening for hydraulic jacking, but it was discovered that the index could be useful in other applications as well. It prominently illustrates the pressure built-up, and could be used to monitor the progress of the pressure build-up during the grouting as well as identifying hydraulic jacking during grouting. In Norway, the most important aspect in the stop criteria today is reaching a pre-defined stagnation pressure (the grout flow must be close to zero), or a pre-defined pressure with a flow beneath a certain value. By using the pre-defined pressure and flow, the PF index representative for the stop criterion can be calculated. In Fig. 10, the stop criterion related to pressure and flow is marked in grey. As the PF index reaches the grey level the criterion is reached. In this case the stop criterion is set to be a grouting pressure of 80 bar, with a

Fig. 10. Pressure and flow over time with the accompanying PF index beneath. The bar on the PF index is marking onset of hydraulic jacking (HJ).

flow of 5 l/min or less. The pressure built-up is getting close to the stop criterion, but what appears to be a severe hydraulic jacking aborts the pressure build-up phase, and the grouting continues at a significant lower pressure.
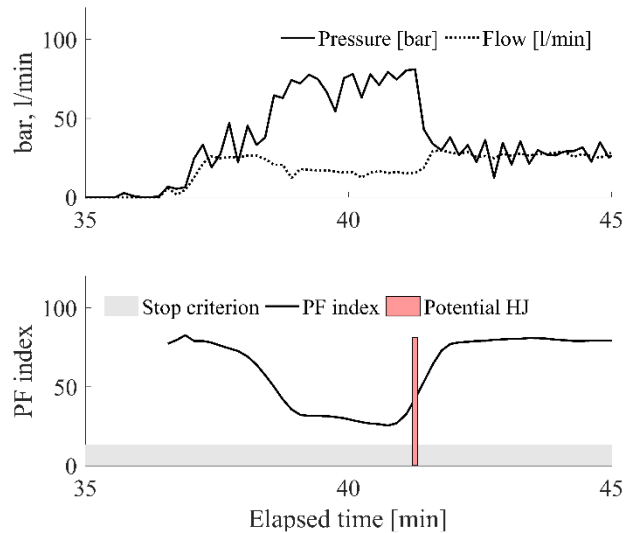
6. Discussion

The main challenges in this study were handling data generated from low sampling frequencies in combination with piston/plunger pumps and unknown geometry of the fracture system. It was therefore necessary to develop an appropriately adapted method for the available data in this project, which has a sampling frequency of approximately once every 10th second. If the method is to be used for other sampling frequencies, it must be carefully adapted. As discussed in the description of the method development, there are several factors that need to be taken into account, such as adjustments made by the operator, fluctuations caused the pumping cycle on the rig and rheological attributes when the grout is pushed from standstill to flowing. Trials of the algorithm show that in most cases all these factors are eliminated when the algorithm is detecting jacking, but it has not been possible to eliminate all the different varieties of disturbance, that might lead to wrongful interpretation of hydraulic jacking. The absolute most challenging aspect of this study has been interpreting hydraulic jacking at lower pressure, because in cases where the grout is filling an open fracture, the pressure does not respond as pronounced. This can result in false positive jacking events in open fracture systems with a high grout take. In further analyses, parameter analysis will be performed to see if it is possible to discover how the events recorded at lower pressure behave, compared to those recorded at higher pressure.

Despite all the discussed constraints, the testing of the method to detect the onset of hydraulic jacking has been successful in regard to the presented theoretical assumption of when hydraulic jacking can be assumed, and the method seems well suited for the further plan to perform a large-scale analysis of hydraulic jacking events occurring in Norwegian tunnelling projects. Currently it is not possible to verify the method directly to provable occurrences of hydraulic jacking during rock mass grouting, because there are no available methods to register these events. Therefore, the developed algorithm and the PF index is theoretical, it is developed through findings from the literature study, study of hydraulic fracturing tests, the simulations with the 2D numerical model and the study of grouting logs from pre-excavation grouting in rock mass in Norway.

As the future logging equipment and grouting rigs are developing, the interpretation of grouting behaviour will be less challenging and give more exact interpretations of the grouting behaviour and performance. During this development, it is also reasonable to believe that the operation of the grouting progress in the field could be more computerized and less operator dependent. Also, the rig could be monitored from office and the grouting procedure adapted to the site, dependent on the continuous collected data.

7. Conclusion

Recognising hydraulic jacking during rock mass grouting and the making of an algorithm to perform computerized detection of hydraulic jacking in grouting logs proved to be a challenging task, because of low sampling frequencies in combination with piston/plunger pumps and unknown geometry of the fracture system. The study concluded that the best way of detecting events with hydraulic jacking is focusing on increasing or stable flow while the pressure is decreasing, alternatively a decreasing or stable pressure while the flow is increasing. Events that were found to cause risk for false positive interpretation of hydraulic jacking are the following:

1. Grout pushed into motion after standstill
2. Operator decreasing or increasing the flow at a rapid rate
3. Fluctuations caused the pumping cycle on the rig
4. Erosion of fracture infilling or bursting through fracture infilling blocking the flow path

5. Grouting with low pressure, in an open fracture system

The issues presented in point 1-3 were mainly solved in the algorithm, but point 4-5 needs to be further investigated by interpretation of grouting behavior during different events.

Despite all the discussed constraints, the testing of the method to detect the onset of hydraulic jacking has been successful in regard to the presented theoretical assumption of when hydraulic jacking can be assumed and the method seems well suited for the further plan to perform a large-scale analysis of hydraulic jacking events occurring in Norwegian tunnelling projects. In future publications, the results generated from the algorithm will be compared to geological parameters, theoretical assumptions on when hydraulic jacking will occur, type of grout, grout consumption and time usage.

During the development of the method a new parameter was created, called the PF index. The index is a dimensionless number, representing the relation between flow and pressure during grouting. It was found to be useful when screening for hydraulic jacking, general interpretation of the grouting progress and could work as a target value, if the grouting criterion is based on reaching a pre-defined pressure at a pre-defined flow rate.

Detection of hydraulic jacking and collection of data related to these events will give valuable information that could contribute to the understanding of such events during rock mass grouting. Identification of incidents of hydraulic jacking during grouting would be a valuable tool for adapting the grouting procedure to the actual site conditions. The matter of which hydraulic jacking should be avoided or not is not within the scope of this article.

Acknowledgements

References

ASTM International, 2004. D 4645 – 04 Standard Test Method for Determination of the In-Situ Stress in Rock Using the Hydraulic Fracturing Method. ASTM International.

Eriksson, M., Friedrich, M., Vorschulze, C., 2004. Variations in the rheology and penetrability of cement-based grouts—an experimental study. Cement and Concrete Research 34, 1111-1119, https://doi.org/10.1016/j.cemconres.2003.11.023

Ghafar, A., Mentesidis, A., Draganovic, A., Larsson, S., 2016. An Experimental Approach to the Development of Dynamic Pressure to Improve Grout Spread. Rock Mechanics and Rock Engineering 49, 3709-3721, https://doi.org/10.1007/s00603-016-1020-2

Gothäll, R., Stille, H., 2009. Fracture dilation during grouting. Tunnelling and underground space technology 24, 126-135, https://doi.org/10.1016/j.tust.2008.05.004

Lombardi, G., Deere, D., 1993. Grouting design and control using the GIN principle. International Water Power & Dam Construction.

Morris, J.P., Chochua, G.G., Bogdan, A.V., 2015. An efficient non-newtonian fluid-flow simulator for variable aperture fractures. The Canadian Journal of Chemical Engineering 93, 1902-1915, https://doi.org/10.1002/cjce.22314

Rafi, J.Y., 2014. Study of Pumping Pressure and Stop Criteria in Grouting of Rock Fractures, Department of Civil and Architectural Engineering. KTH Royal Institute of Technology, Stockholm.

Rafi, J.Y., Stille, H., 2014. Control of rock jacking considering spread of grout and grouting pressure. Tunnelling and Underground Space Technology 40, 1-15, https://doi.org/10.1016/j.tust.2013.09.005

Stille, H., 2015. Rock Grouting -Theories and applications. BeFo, Stockholm.

Strømsvik, H., Grøv, E., 2017. Interpretation of Pressure and Flow During Pre-Grouting in Hard Rock Tunneling, Grouting 2017: Case Histories. ASCE, Honolulu, USA, pp. 285-294, https://doi.org/10.1061/9780784480786.028

Tunbridge, L., Aarset, A., Tønnessen, E., 2014. FoU prosjekt med måling av injeksjonstrykk in situ, Fjellsprengningsdagen. NFF, Oslo, pp. 31.31-31.13.

Warner, J., 2004. Practical handbook of grouting: soil, rock, and structures. John Wiley & Sons.