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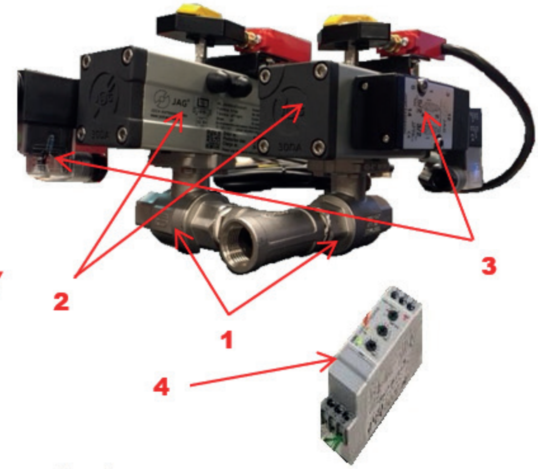

1. Ball-valves, 2. Pneomatic actuators,
3. Solenoid valve, 4. Asymmetrical recycler timer

DEVELOPMENT OF DYNAMIC GROUTING STAGE 1

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Almir Draganovic
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BeFo Report 197

Cover figure: Schematic view of VALS: 1) gas container, 2) pressure regulator, 3) load cell, 4) grout tank, 5) pressure transducers, 6) DAQ

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Utveckling av dynamisk injektering Etapp 1

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PREFACE

Sealing of underground infrastructure is an essential part of construction. Requirements for sealing are becoming larger and especially for projects in urban areas. New technologies and materials are needed to achieve these increased demands and dynamic grouting is an attempt to develop the grouting technology. We want to improve penetration ability and spread of the grout in rock fractures by application of varying grouting pressure instead of constant pressure. Dynamic grouting can affect the flow character and viscosity and thereby reduce plug formation of the grout. In this project, a series of experiments in laboratory with long slot with varying aperture have been performed. The experiments show that we can get a better penetration into narrow slots when we apply varying pressure.

The research has had support from a reference group consisting of Mats Holmberg (Tunnel Engineering), Peter Ulriksen (LTH), Diego Mas Ivars (SKB), Per Tengborg (BeFo), Håkan Stille (KTH) and Johan Wiklund (RISE, Incipientus Ultrasound Flow Technologies).

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FÖRORD

Tätning av undermarkinfrastruktur är en väsentlig del vid byggande. Krav på tätning blir alltmer större och speciellt för projekt i urbana områden. Det behövs nya tekniker och material för att nå dessa krav och dynamisk injektering är ett försök att utveckla injekteringstekniken. Man vill kunna förbättra inträngningsförmågan och spridningen av bruk i bergsprickor genom att använda varierande injekteringstryck i stället för konstant tryck. Dynamisk injektering kan påverka flödets karaktär, minska viskositeten och därmed minska pluggbildning av bruket. I detta projekt har en serie av försök i laboratoriet med lång spalt med varierade spaltvidder genomförts. Försöken visar att man kan få en bättre inträngning i smala spalter när vi applicerar varierande tryck.

Forskningen har stöttats av en referensgrupp bestående av Mats Holmberg (Tunnel Engineering), Peter Ulriksen (LTH), Diego Mas Ivars (SKB), Per Tengborg (BeFo), Håkan Stille (KTH) och Johan Wiklund (RISE, Incipientus Ultrasound Flow Technologies).

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SUMMARY

A major concern in any underground infrastructure is to provide and maintain the sealing required, first during the construction phase, and then during the service life of the project. In the construction phase, the water ingress into the construction area increases the duration and the costs of the project. In some occasions, it might even lead to environmental issues such as lowering the groundwater tables, settlement of the surface structures, and destruction of the vegetation. It can sometimes be even harmful to the human life. A typical example for that can be the icicle falls on passing vehicles in the road tunnels in the winter. Some other disadvantages can be decreasing the duration of the service life of the projects and increasing the maintenance costs. To provide the required sealing, one of the most significant factors is to obtain enough spread of grout in the fractures surrounding the facility. This can be achieved using cement-based grouting, which is probably the most frequently used technique in the industry due to the lowest costs and environmental issues. However, in the cement-based grouting, the spread of grout in fractures is disrupted due to the filtration of the cement particles at the constrictions especially in constrictions smaller than 100 μm. This leads to inadequate spread of grout in such fractures and consequently insufficient sealing.

The presented report is a summary of the laboratory investigation conducted in collaboration between RISE CBI Betonginstitutet and Division of Soil and Rock Mechanics, KTH Royal Institute of Technology during 2017-2018 with the aim to improve the grout spread in rock fractures using dynamic grouting technique. The dynamic grouting, which has been developed to improve the spread of grout in rock fractures, has been studied in both the lab and the field since 1985. The focus of all the previous investigations was however on application of high-frequency oscillating pressure to reduce the grout apparent viscosity. This was achieved by destructing the grout internal structure and reconstructing to a lower viscosity suspension. Even though some improvements were reported in the corresponding literature, the major remaining issue was yet quick dissipation of the oscillations along the fractures and consequently inadequate spread of grout.

Recent investigation performed by the authors, presented in BeFo-Report-149, illustrated a significant improvement (up to 11 times) in the total volume of grout passed through the apertures smaller than 70 μm in a short slot by applying low-frequency rectangular pressure impulses compared to the static pressure. In this study, the mechanism of improvement of the grout spread was interpreted as successive erosion of the produced filter cakes due to the variation in flow pattern at the constrictions caused by the pressure change in consecutive cycles. However, since the laboratory experiments conducted in this study were carried out using a short slot, the dissipation length of the applied pressure impulses along a longer fracture was yet questionable.

The present study first aimed to investigate the dissipation of the dynamic pressure impulses along a much longer artificial fracture, so-called varying aperture long slot (VALS). The investigation was conducted by applying two selections of the peak/rest periods in two steps. In each step, the extent of the improvement of the grout spread was examined in different pressure conditions. The main difference between the two steps was the pressure source. A high-pressure gas tank and a screw pump were the two variants of the pressure source that were used in step 1 and step 2, respectively. Even though the project was a limited study based only on the laboratory experiments, the results obtained in terms of both the extent of improvement of the grout spread and the extent of dissipation along a fracture were promising showing the potential of the method. Finally, the study suggests further development of the method to full scale field tests, to demonstrate the capacity of the new technique to the stakeholders in industry.

KEYWORDS

Cement-based grout, Filtration, Varying Aperture Long Slot-VALS, Dynamic grouting,
Low-frequency rectangular pressure impulse

SAMMANFATTNING

Ett stort problem i infrastrukturprojekt under mark är att åstadkomma och behålla den tätning som krävs, först under byggnadsfasen och sedan under konstruktionens livslängd. Under byggnadsfasen ökar vatteninflödet i byggkonstruktionen vilket leder till ökade produktionskostnader och i vissa fall till miljöproblem såsom sänkning av grundvattennivå, sättningar och förstöring av vegetation. Ibland kan det vara skadligt även för människor. Ett typiskt exempel på det är när istappar faller på passerande fordon i vägtunnlarna under vintern. Andra nackdelar kan givetvis vara en minskning av projektets livslängd och ökad underhållskostnad. För att åstadkomma den nödvändiga tätningen en av de viktigaste faktorerna som måste uppnås är tillräcklig spridning av bruk i bergmassan som omger anläggningen. Detta kan uppnås med cementbaserad injektering. Det är förmodligen den vanligaste metoden inom industrin på grund av låga kostnader och låg miljöpåverkan. Dock är spridningen av bruket i sprickor begränsad på grund av filtreringen av cementpartiklarna vid förträngningarna, speciellt vid förträngningar mindre än 100 μm. Detta leder till otillräcklig spridning av bruket i sprickor och otillräcklig tätning.

Den presenterade rapporten är en sammanfattning av laboratorieundersökningen genomförd på KTH, Avdelningen för jord- och bergmekanik i samarbete med RISE CBI Betonginstitutet under perioden 2017–2018, med syfte att förbättra injekteringen av bergmassa med dynamisk injekteringsteknik. Den dynamiska injekteringen har studerats både i laboratoriet och i fält sedan 1985. Fokusen på alla tidigare undersökningar var emellertid tillämpningen av högfrekvent oscillerande tryck för att minska viskositeten genom att påverka brukets inre struktur. Trots att vissa förbättringar rapporterades i litteraturarten är den stora frågan om en snabb dämpning av vibrationerna längs sprickor och följaktligen otillräcklig spridning av bruk var kvar.

En nyligen genomförd undersökning av författarna, som presenterades i BeFo-Report-149, illustrerade en signifikant förbättring (upp till 11 gånger) mätt i den totala volymen av det passerade bruket. Bruket provades med öppningarna mindre än 70 μm i en kort spalt där man tillämpade lågfrekventa rektangulära tryckimpulser och statisk tryck. I denna studie tolkades förbättringsmekanismen som erosion av partiellbyggda filterkakor som orsakades av varierande flödeskaraktär i konsekutiva cykler. Eftersom laboratorieexperimenten i denna studie utfördes med en kort spalt var emellertid dämpning för de applicerade tryckimpulserna längs en längre spricka ifrågasatt.

Den föreliggande studien syftar till att undersöka dämpningen av de dynamiska tryckimpulserna längs en mycket längre artificiell spricka med varierade spaltvidder (VALS). Detta provades genom att man tillämpade två olika tryckformer av topp/viloperioder och i två steg. I varje steg undersöktes även förbättringen av brukets inträngningsförmåga under olika tryckförhållanden. Den huvudsakliga skillnaden mellan de två stegen var tryckkällan. En högtryckstank och en skruvpump var de två varianterna av tryckkällan som användes i steg 1 respektive steg 2. Trots att projektet var en begränsad studie, baserad endast på laboratorieexperimenten, visade det en förbättring både med avseende på brukets inträngningsförmåga som graden av tryckdämpningen längst en spricka. Metoden är lovande och har potential. Slutligen föreslår studien en vidareutveckling av metoden till fullskaliga fälttester för att påvisa kapaciteten hos den nya tekniken för intressenterna inom industrin.

NYCKELORD

Cement-baserad injekteringsmedel, Filtration, Varying Aperture Long Slot-VALS, Dynamisk infektering, Lågfrekvent rektangulär tryckimpuls

TABLE OF CONTENTS

1. INTRODUCTION

One of the most significant challenges in any underground infrastructure is to sufficiently seal the area against ingress of water and/or leakage of any gas/liquid stored inside the facility into the surrounding environment. To obtain the sealing required, one of the crucial parameters is to achieve sufficient spread of grout into the surrounding pores and fractures during the grouting operations (Houlsby 1990; Lombardi 2003; Warner 2004; Gustafson and Stille 2005; Fransson 2008; Gustafson et al. 2013; Stille 2015). Among the available alternatives, the cement-based grouts, which are cheaper and not hazardous to the environment, have been considered more reliable by the grouting industry worldwide (Houlsby 1990; Weideborg et al. 2001; Karol 2003; Warner 2004). However, in application of the cement-based grouts, the plug building and filtration of the cement particles, which occurs due to the arching/bridging of the cement particles at a fracture constriction, restricts the grout spread (Eriksson et al. 2000; Eriksson and Stille 2003; Draganovic and Stille 2011). In addition to the filtration and grout penetration ability, the grout's rheological properties (i.e. the viscosity and the yield stress) are the other parameters governing the grout spread (Håkansson 1993; Schwarz 1997; Eriksson et al. 2004; Eklund 2005; Banfill 2006; Eklund and Stille 2008; Rafi 2013; Mohammed et al. 2014). The necessity to obtain sufficient grout spread is more discernible in underground infrastructures with higher sealing demands, such as in nuclear/toxic waste repositories, which has become one of the major concerns in Scandinavia and especially in Sweden during the last decade (Pusch et al. 2012). Accordingly, one of the associated issues is insufficient grout spread within the fractures with apertures smaller than 100 μm. This deteriorates the obtained sealing and the resulting durability significantly.

A survey conducted in several tunnel projects in Sweden has revealed that in hard rock with good to very good quality, grouting was required within a range of 176-368 m^3 of the injected grout per km of the tunnel length. This shows the high relevance of a more efficient grouting technique for reduction of the costs, the environmental impacts, and the sustainability issues specially in large-scale projects.

1.1 Background

Several years of the laboratory investigations and the field works related to grouting have shown that one of the factors influencing the grout filtration tendency and rheological properties and thereafter the spread of grout in fractures is the applied pressure. A sufficient increase in the applied pressure decreases the filtration tendency and improves the grout spread by increasing the potential for erosion of the unstable filter cakes produced at a fracture constriction (Eriksson et al. 1999; Hjertström 2001; Draganovic and Stille 2011, 2014; Stille et al. 2012). Nobuto et al. (2008) showed that a stepwise pressure increment decreases the potential for clogging of the cement particles at the entrance of a fracture. Pusch et al. (1985) were probably the first, who demonstrated the influence of high-frequency oscillating pressure on improving the grout spread during their investigation conducted in the Stripa mine. Borgesson and Jansson (1990) continued the previous researches by further examining a high-frequency large-amplitude oscillating pressure superimposed on an underlying pressure of 20 bar. They illustrated that in such pressure condition even a low water content cement grout can penetrate well through 100 μm artificial fractures. The latter described the associated mechanism of action as reduction in the grout viscosity due to the application of high-frequency oscillation, whereby the grout's internal structure was disrupted and reorganized to provide a lower viscosity suspension. Wakita et al. (2003) also investigated the same method using oscillating amplitudes of up to 5 bar superimposed on an underlying pressure of 10 bar and in similar fashion obtained an increase in the flow rate and the total volume of grout take. Afterwards, Mohammed et al. (2015) further elaborated on the method and once again recognized it as a possible solution to improve the grout spread.

Despite the promising results obtained using high-frequency oscillating pressure compared to the static pressure, use of dynamic pressure impulses has not yet been established as a common method in grouting practice in industry, due to the limited efficiency and quick dissipation of the oscillation along a fracture. To increase the efficiency of the method and reduce the dissipation of the pressure impulses along a fracture, the authors introduced a low-frequency rectangular pressure impulse in contrast to the previous efforts (BeFo reports 149 and 181). The idea was to better control the filtration by successive erosion of the produced filter cakes at a fracture constriction. This could be obtained by continuous variation in the flow pattern in consecutive cycles caused by the corresponding pressure change. The ultimate goal was to effectively improve the grout spread in micro-fractures, especially with apertures < 70 μm. The results obtained showed significant improvement of up to 11 times in the total volume of grout take in 30-43 μm apertures in the experiments conducted using a short slot (Ghafar et al. 2016). Afterwards, Ghafar et al. (2017) studied the dissipation of the pressure impulses in a considerably longer artificial fracture (i.e. varying aperture long slot-VALS) with 4-m length and apertures of 230-10 μm. The results revealed that the remaining amplitudes of the pressure impulses at distances of 2.0 m and 2.7 m from the source (with apertures of 230-70 μm and 230-50 μm) were as large as 46% and 25% of the initial applied amplitude, respectively. However, due to some limitations in the equipment, the latter could not yet determine the extent of the improvement in the total volume of grout passed through the apertures smaller than 70 μm. In other word, none of the previous studies could be considered sufficiently comprehensive for drawing the conclusions that dynamic pressure impulses effectively improve the grout spread in grouting operations. Issues of significance were nevertheless how quickly the dynamic pressure impulses dissipate from the source (the pump) along a fracture and how much the dynamic pressure impulses can improve the corresponding grout spread in fractures < 70 μm.

1.2 Objectives and scope of work

The main objective of this study was to determine if the dynamic pressure impulses can be used to effectively improve the spread of cement-based grout in rock fractures. Thus, the following questions were aimed to address:

- To what extent can dynamic pressure impulses affect the grout spread in micro-fractures < 70 μm?
- How quickly do the dynamic pressure impulses dissipate from the source to the grout front along an artificial fracture with variable aperture?

The study was a supplement to two previous BeFo projects, reported in BeFo reports 149 and 181. The aim was to further investigate the influence of using low-frequency rectangular pressure impulse to improve the spread of grout compared to that using static pressure. The investigation was conducted using a 4-meter long artificial fracture (so-called VALS) recently developed by the authors. Two compositions of the peak/rest periods (i.e. 2 s/2 s and 1 s/5.5 s) were examined to determine whether they show considerably different impacts, where the spread of grout within the apertures narrower than 70 μm was the principal target. In the first step, the setup used for providing the dynamic impulses from the static pressure was replaced with a new design. The reason for that was to provide a better control on the dynamic impulses in order to address the equipment related limitations observed in the previous stages of the project. In this step, the pressure source was still a high-pressure gas tank (in a closed system with limited grout tank capacity). In the second step, the pressure source was changed from a gas tank to an eccentric screw pump (in an open system using a much larger open-surface grout tank with an agitator) to increase the grout volume available for grouting. In both steps, the total volume of grout passed through apertures < 70 μm at static and dynamic pressure conditions as well as the dissipation of the pressure impulses along the VALS were examined and the associated filtration and erosion phenomena were studied. The results obtained are anticipated to provide a basis for the next stage of the project (Stage 2), in which the efficiency of the method is intended to be upscaled and demonstrated in a couple of large-scale field tests.

1.3 Limitations

Some of the main limitations that the authors confronted in this study are summarized as follows:

1.3.1 Number of test repetitions

The first limitation that can be considered in this study is the limited number of experiments conducted in each step. Nevertheless, based on our engineering judgement and understanding of different phenomena involved, the number of test repetitions conducted was considered acceptable for the conclusions drawn in the framework of the project.

1.3.2 Equipment

Concerning the equipment, the following limitations can be distinguished among others:

- Despite the fact that the shape and the geometries of VALS, the artificial fracture used in this study, were more realistic than the other available test equipment, yet it was associated with noteworthy limitations. Among those, the most significant ones are the limited number of the constrictions, the sharp variation of the apertures, the surface roughness of the steel plates, and the distance between the constrictions. Furthermore, the distribution of the apertures can probably be considerably different from the irregularities that might exist in a real fracture in rock. In addition, due to the inherent design of VALS, the method is only applicable to study the grout flow in 1D (one-dimensional) flow condition.
- The maximum capacity of the grout tank used in the first step of the study (using gas tank as pressure source in a closed system) was only 2.6 l with no agitating system. In this step, despite the enhancement adjusted on the valve system used for producing the

dynamic pressure impulses, yet we had some discharge of grout out of the system in each cycle. Consequently, having a larger grout tank could be beneficial to better determine the extent of the improvement in the total volume of grout passed through the apertures smaller than 70 µm.

- The screw pump that was selected in the second step of the study instead of a piston pump was to provide a stable static pressure without fluctuations that were associated with the piston pump. This stable static pressure was supposed to change to a designated dynamic pressure using a valve system controlled by pneumatic actuators and solenoid valves. Unfortunately, the maintenance of the selected pump was very time-consuming and difficult. After each test all the pump's components that were in direct contact with grout should be dismantled, washed, dried, lubricated, and reinstalled again, otherwise without proper care the pump could be destroyed.
- An automatic pressure control valve that was added to the system right after the pump's outlet was a crucial component of the system in the second setup. Its action was to help stabilizing/counterbalancing the pressure in the case of filtration and/or erosion of the cement particles. Unfortunately, this valve was completely destroyed in the first test due to uneven filtration of the cement particles (in only one side of the opening). In the following tests, the control valve was replaced with a manual one. However, it could not act as anticipated and by increasing the filtration and/or erosion some fluctuation in pressure was observed along the experiment.
- Limited number of the pressure sensors (only three) along the VALS caused by the limited number of channels in data acquisition system (DAQ) was another limitation that can be improved in the future experiments.

These limitations should be carefully considered when drawing the respective conclusions and planning for further tests.

1.3.3 Technical

To better understand the filtration and erosion phenomena and to identify how dynamic impulses improve the grout spread in VALS, it was an advantage if we could observe the flow pattern of the grout passing through the constrictions. Accordingly, use of transparent materials, e.g. Plexiglas or Polycarbonate sheets in the production of VALS could be beneficial. However, this was found impossible due to the limited bending capacity of the transparent sheets to withstand against 15 bar pressure.

1.4 Organization of the report

After presenting a short introduction, the background, the main objectives, the scope of work, and finally the main limitations associated with this study are presented in chapter 1. Chapter 2 is dedicated to evaluation of the influence of the dynamic pressure impulses applied in VALS with pressurized gas as pressure source (in a closed system) using a newly developed setup for providing dynamic impulses from static pressure. Chapter 3 presents further development of the experimental apparatus, to evaluate the influence of the dynamic pressure impulses applied in VALS but using a screw pump as pressure source with a much larger grout tank and an agitator in an open system. Planned future work and recommended projects are then presented in chapter 4. Finally, references are listed in chapter 5.

2. Development of dynamic grouting using pressurized gas (Step 1)

2.1 History of the problem

Cement-based grout is the most frequently used material in rock grouting. The main issue though is the grout filtration tendency caused by arching/bridging of the cement particles at the fracture constrictions that restricts the grout spread. The grout rheological properties, i.e. the viscosity and yield stress, are the other factors governing the grout spread. These grout properties are, however, influenced by several parameters the most significant of which are the applied pressure, water-to-cement ratio, cement grain size and distribution curve, and the additives and admixtures included in the grout formulation. Accordingly, this study is focused on the influence of the applied pressure on improving the grout spread.

As described by Müller and Bruce (2000), the grouting pressures provided by almost all contemporary grouting pumps such as progressive cavity pumps, piston pumps, or plunger pumps are to some extent associated with some fluctuations. The progressive cavity pumps have, however, shown the least fluctuation in the output pressure in comparison to the others that can be considered as nearly constant (Bruce 1992; Müller and Häny 2000). There has been a controversy among the experts, whether the grouting operations should be preferably conducted at either of the constant or dynamic pressure conditions (Bruce 1992). According to Weaver and Bruce (2007), in the old “North American” grouting philosophy, application of constant pressure that can be principally provided by progressive cavity pumps was preferred. However, in the new “North American” and “European” grouting philosophies, application of slightly fluctuated/dynamic pressure that can be inherently provided by the piston and plunger pumps is encouraged (Weaver 1991; Bruce and Dugnani 1994; Bruce 2013). Müller and Bruce (2000) suggested that in the piston and plunger pumps, the sudden pressure drop occurs within each cycle might be advantageous. That was due to encouraging the cement particles and clusters to reorient and conform to the constrictions within the fracture. Application of high-frequency oscillating pressure has been shown to improve the grout spread in fractures, both in lab and field, by reducing the grout apparent viscosity (Pusch et al. 1985; Borgesson and Jansson 1990; Wakita et al. 2003; Mohammed et al. 2015). This method has however not yet been industrialized due to the quick dissipation of the oscillation along a fracture and limited efficiency.

To address the associated issues, in a recent investigation carried out by Ghafar et al. (2015, 2016), a low-frequency rectangular pressure impulse was introduced and examined as a new alternative. The aim was to improve the grout spread by successive erosion of the produced filter cakes at a fracture constriction in consecutive cycles. The mechanism of improvement was interpreted as variation in flow pattern due to the change of pressure and thereupon flow velocity. The results obtained during the experiments conducted using a short slot with 30 and 43 µm apertures revealed a substantial improvement of up to 11 times in the total volume of grout spread compared to that in the experiments conducted at static pressure condition. The dissipation of the pressure impulses was then investigated by Ghafar et al. (2017) along a considerably longer artificial fracture (so-called VALS with 4 m length and 230-10 µm apertures). The goal was to study the filtration and erosion phenomena at different constrictions and evaluate the extent of the dissipation of the pressure impulses along the slot. The latter showed that the dissipation of the pressure impulses, even after 2.0

and 2.7 m distances from the slot's beginning (apertures of 230–40 μm) was not substantial and the remaining amplitudes of the impulses were considered adequate for counterbalancing/eroding the filtration of the cement particles occurred at the constrictions to extend the grout penetration.

As described in BeFo report 181, the pressure source employed in all the experiments conducted previously by Ghafar et al. was a high-pressure gas tank of 200 bar used in a closed system. Using a pressure regulator, the applied pressure was however reduced to a predefined value of 15 bar and kept constant to force the grout through the system at a static pressure condition. In order to change the provided static pressure to a programmable dynamic one, a three-way ball valve coupled with a control unit was employed in the test setup to regulate the pressure at the beginning of VALS. This setup was however not working as anticipated due to some limitations related to inherent design of the ball valve. During each experiment, when the valve was rotating between its two predefined positions to switch the grout flow and provide the dynamic impulses in each cycle, there was a moment that all three ways of the valve were partially connected allowing a considerable amount of grout to discharge out of the system. Consequently, each experiment was terminated relatively quick (after complete discharge of the grout tank) before the latter could properly evaluate the extent of the improvement in the total volume of grout passed through the apertures < 70 μm.

To address this issue in the first step of the current study, the three-way ball valve used in the previous setup was replaced with a newly designed system consisted of two two-way ball valves each of which was equipped with a pneumatic actuator, a solenoid valve, and an asymmetrical recycler timer. The aim was to better control the system and close the first valve shortly before opening the second one.

2.2 Selection of the peak and rest periods

As presented in BeFo report 181, the peak and rest periods used in the previous stage of the project for the pressure impulses applied in the experiments conducted on VALS was only 2 s/2 s. To improve the efficiency of the system in the current study after several preliminary experiments, we realized that to reduce the potential of filtration of the cement particles in each cycle, the duration of the peak period should be reduced to a minimum of 1 sec. On the other hand, to increase the potential of erosion in each cycle, the duration of the rest period should be increased to a maximum of approximately 5.5 sec. These values were experimentally obtained since by having shorter peak period the pressure applied at the beginning of the slot could not reach the designated value of 15 bar and by having a longer rest period the extent of the pressure drop in each cycle could be disregarded. Accordingly, the peak and rest periods that were selected to apply in the first stage of this study were 2 s/2 s and 1 s/5.5 s, respectively (Fig. 1).

As seen in figure 1 (to the right), the peak period of 1 second is the duration that the first valve (more details can be found in the description of the test apparatus) is kept open and the grout flow is directed towards the slot, whereas the second valve is closed. The next 3.5 second that a gradual pressure drop occurs is the period that both valves are closed, and the pressure reduction occurs only because of penetration of the grout through the slot. The sudden pressure drop that occurs afterwards (towards zero) happens when the second valve is opened (only for 0.1 second) to release/exhaust the remaining pressure to the outside of the system. Then, the second valve is closed for approximately 1.9 second until the next cycle is initiated. In this way, the peak and rest period of 1 s/5.5 s was provided to apply during the experiments.

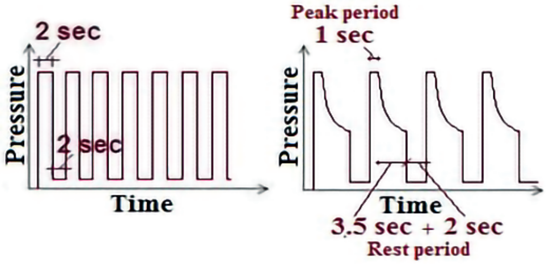

Fig. 1, The peak and rest periods applied in each cycle in step 1

2.3 Materials, mixing process, and test plan

The grout used in the experiments in this study was one of the most frequently used recipes in the grouting industry in Sweden consists of INJ30 from Cementa AB with d95 of 30 µm (i.e. 95% by weight of the cement particles were smaller than 30 µm) as cement with a water to cement ratio (w/c) of 0.8, together with iFlow-1 from Sika AB with 0.5% concentration (by weight of cement) as super-plasticizer.

A high-speed rotor-stator dispersion system from VMA-GETZMANN GMBH (SR series) with 10,000 rpm was used as the main mixer for the mixing process in this study. The mixing time was 4 minutes in all experiments started by adding the scaled cement samples to the required water. A handy-mixer was however first utilized to pre-mix the materials before starting the main mixing process. After 2 minutes of the mixing, the scaled super plasticizer was added to the mixture. This was to facilitate the dispersion of the cement particles and clusters in the grout suspension to improve the grout penetrability properties. By finishing the mixing process, the grout container (with approximately 2.6 l capacity) was filled with the mixed grout immediately to run the respective test without delay in order to prevent any potential segregation/settlement.

The experiments were then conducted at both static and dynamic pressure conditions with a maximum pressure of 15 bar, according to the test plan presented in Table 1. The idea was to investigate the influence of dynamic pressure on improving the grout spread compared to that in the static pressure condition and to examine whether different setups of dynamic impulses can enhance the efficiency substantially.

As seen in table 1, the experimental program in step one of this study consisted of three groups. In test group C, two experiments were conducted at static pressure condition (15 bar pressure). Afterwards, the experiments were continued in test group D1 and D2, when a rectangular pressure impulse with a maximum of 15 bar was employed to improve the grout spread using 2 s/2 s and 1 s/5.5 s peak and rest periods, respectively.

Table 1 Test plan (Step 1)

Test group	Number of tests	Pressure type	Peak/rest period (sec)
C	2	Static	-
D1	2	Dynamic	2 s/2 s
D2	2	Dynamic	1 s/5.5 s

2.4 Test apparatus, procedure, and evaluation methods

The test setup used in step 1 of this study consisted of a 2.6-l capacity grout tank suspended from an S-shaped load cell (RSCC C3/50kg from HBM) to register the weight of the grout over time (Fig 2). The pressure source used was a 200-bar high-pressure gas tank that using a regulator reduced and maintained the pressure at 15 bar along the entire experiment. Right after the regulator, a pressure sensor was allocated to control the pressure applied to the grout tank continuously. To mimic the grouting process in a sufficiently long artificial fracture, the varying aperture long slot (VALS) developed by Ghafar et al. (2017) was then connected to the grout tank. In order to change the provided static pressure to dynamic with programmable duration of the peak and rest periods, two two-way ball-valves equipped with pneumatic actuators, and solenoid valves were installed right before the entrance of VALS (Fig. 2, 3). The solenoid valves were controlled by three coupled asymmetrical recycler timers. The VALS itself was equipped with pressure sensors, P1–P3, to register the pressure variation at 2.7, 2.0, and 0.0 m from the slot's beginning, respectively, to study the dissipation of the pressure impulses and the filtration and erosion processes along the slot.

In each experiment, first the duration of the peak/rest periods should be set using the asymmetrical recycler timers. After filling the grout tank with the mixed grout, the tank should be pressurized to 15-bar, while both valves 1 and 2 at the entrance of VALS were closed. To initiate the test, the timers had to activate the first solenoid valve and consequently the first actuator in order to open valve 1 allowing the grout flow towards the slot, while valve 2 was yet closed. After the predefined peak period, valve 1 was closed and shortly after that valve 2 was opened to release the VALS's internal pressure to the atmospheric pressure (approximately zero) at the beginning of the slot. The result was a gradual pressure decrease followed by a sharp drop in pressure over the rest period. This process was repeated in consecutive cycles until the flow stopped (due to the filtration at the constriction along the slot) or complete discharge of the grout tank.

In order to investigate the dissipation of the pressure impulses along the VALS, the amplitudes of the pressure variation registered by P1–P3 at different locations were considered for comparison, when the pressure impulses were stabilized. In addition, the min- and the max-pressure envelopes were used to monitor the evolution of filtration and erosion in consecutive cycles, as described in BeFo reports 149 and 181. These envelopes were the polylines connecting the minimum and the maximum pressures obtained in consecutive cycles, respectively (See BeFo reports 149, 181). Over these envelopes, any upward and downward trends were representative for the filtration and erosion processes, respectively. Finally, the total volume of grout passed through the apertures smaller than 70 µm at dynamic pressure conditions were registered and compared with that in static pressure tests.

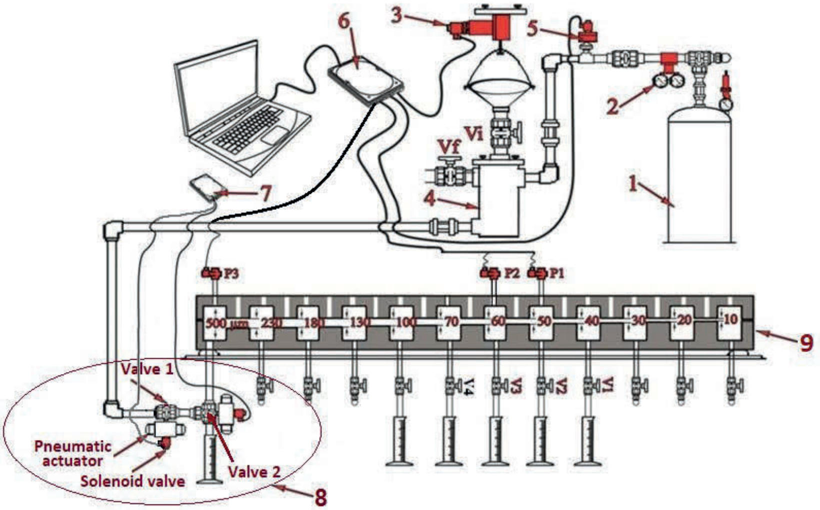

Fig. 2 Schematic view of the test set-up: 1) Gas tank, 2) pressure regulator, 3) load cell, 4) grout tank, 5) pressure sensor, 6) DAQ-data acquisition system, 7) 3 coupled asymmetrical recycler timers, 8) 2 two-way ball-valves with pneumatic actuators, and solenoid valves, 9) VALS (Ghafar et al. 2017b)

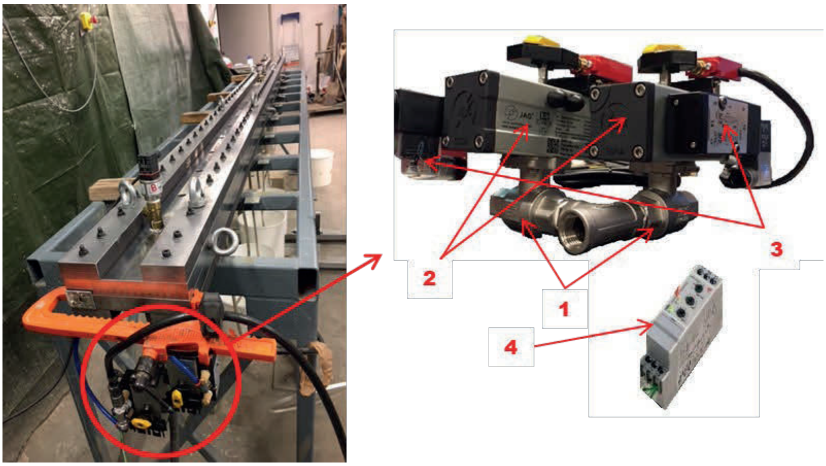

Fig. 3 Figures of the new system used to change the applied static pressure to dynamic: 1) Ball-valves, 2) Pneumatic actuators, 3) Solenoid valve, 4) Asymmetrical recycler timer

2.5 Summary of the results and discussion

In step 1 of this study, we primarily aimed to investigate the influence of dynamic impulses on improving the grout spread compared to that in the static pressure condition. The investigation was conducted at 2 s/2 s and 1 s/5.5 s peak/rest periods. The objective was to study the grout spread within the apertures smaller than 70 µm in VALS. It was also to demonstrate the extent of dissipation of the pressure impulses from the source to the grout front during the injection process. Studying the filtration and the erosion processes at the constrictions throughout the experiments was the other goal of the study.

2.5.1 Improvement of the grout spread in apertures < 70 μm

A summary of the results of the total weight of passed grout obtained from the experiments conducted at both static and dynamic pressure conditions is presented in Table 2. The experiments conducted at dynamic pressure condition were started using 2 s/2 s peak/rest period (group D1). This was because similar experiments were conducted by the authors before, where there was considerable discharge of grout out of the system in each cycle. The reason for that was the limitations in the test setup. Consequently, each experiment was terminated due to complete discharge of the grout tank before we could evaluate the improvement in the total amount of grout passed through the slot. It should be considered though that in those experiments the dissipation of the pressure impulses after 2.0 and 2.7 m from the slot's beginning was not substantial (BeFo report 181).

To address this issue in step 1 of the current study, the setup used was improved and instead of one three-way ball valve, two two-way ball-valves were employed. The aim was to close valve 1 shortly before opening valve 2 to prevent direct grout flow from the grout tank to the outside (Figs. 2, 3). Even though the new system was working much better than the previous design, yet the grout discharge out of the system was considerable in each cycle. That was because of the high pressure inside the VALS and the fact that valve 2 was kept open during the whole rest period (2 sec). Accordingly, the grout tank got empty again before we could obtain adequate grout flow to evaluate the extent of the improvement in the amount of passed grout through the slot. That is why the results of the test group D1 (with 2 s/2 s peak/rest period) are not reported in table 2.

To fix this problem in the next effort (in test group D2 with 1 s/5.5 s peak/rest period), valve 2 was kept open only for 0.1 sec during the whole rest period of 5.5 sec (See section 2.2 for more details). That was to minimize the potential for discharge of grout and to provide sufficient drop of the slot's internal pressure to approximately zero in each cycle.

As seen in table 2, the average weight of passed grout in group D2 conducted using dynamic impulses with 1 s/5.5 s peak/rest period is approximately ten times the result obtained from group C conducted at static pressure condition. This shows the extent of influence of the dynamic impulses applied to improve the grout spread even through such small aperture sizes (40-70 μm) compared to that when the static pressure applied. It is worth mentioning that both tests conducted in group D2 were yet terminated due to the complete discharge of the grout tank, not as a result of filtration of the cement particles along the VALS. The discharge though was mainly occurred through valve 2, similar to group D1, but in a considerably longer period. This suggests that having extra grout available for injection in each test (i.e. having a larger grout tank) could further increase the potential of improvement of the grout spread (i.e. even more than 10 times increase in the average weight of passed grout) at dynamic pressure condition. Accordingly, in step 2 of the study we employed a larger grout tank with an agitator and used a screw pump in an open system to provide a backflow of grout to the tank in each cycle.

Table 2 Improvement on grout spread in apertures < 70 µm obtained under application of dynamic impulses (1s/5.5s) compared to static pressure condition

Test group	Test No.	Peak/Rest period [sec]	Weight of the passed grout [g]					Improvement of grout spread in apertures < 70 µm
			V1 (40 µm)	V2 (50 µm)	V3 (60 µm)	V4 (70 µm)	Average (40-70) µm	
C (Static)	1	-	84	60	0	0	102	-
	2	-	0	0	44	16		
D2 (Dynamic)	1	1 s/5.5 s	0	120	880	-	1020	10.0
	2	1 s/5.5 s	0	76	964	-		

2.5.2 Dissipation of the pressure impulses along the VALS

Fig. 4 shows the results of the pressure-time measurement obtained from one of the experiments conducted in test group D1 using 2s/2s peak/rest period. The dynamic impulses applied at the beginning of the slot with approximately 15 bar amplitude of pressure variation in each cycle (registered by P3) show minor/no changes along the entire experiment. These dynamic impulses further show a dissipation of approximately 69% (registered by P2) over the first 2.36 m of the slot (having apertures of 230-60 µm) at stabilized condition obtained after 75 sec. The pressure impulses finally show a dissipation of approximately 78% (registered by P1) along 2.7 m length of the slot (having apertures of 230-50 µm) at stabilized condition obtained after 120 sec. Accordingly, the analysis shows that when applying dynamic impulses with 2s/2s peak/rest period in VALS, the remaining amplitude of the impulses after 2.36 and 2.7 m can be as large as 31% and 22% of the initial applied amplitudes, respectively.

Fig. 5 shows the results of the pressure-time measurement obtained from one of the experiments conducted in test group D2 using 1 s/5.5 s peak/rest period. The dynamic impulses applied at the beginning of the slot with approximately 10 bar amplitude of pressure variation (between 5 to 15 bar) in each cycle (registered by P3) once again showed minor changes along the entire experiment. These dynamic impulses after stabilizing at 260 sec showed a dissipation of approximately 70% (registered by P2) over the first 2.36 m of the slot. Therefore, the remaining amplitude of the pressure impulses after this length was approximately 30% of the initial applied amplitude.

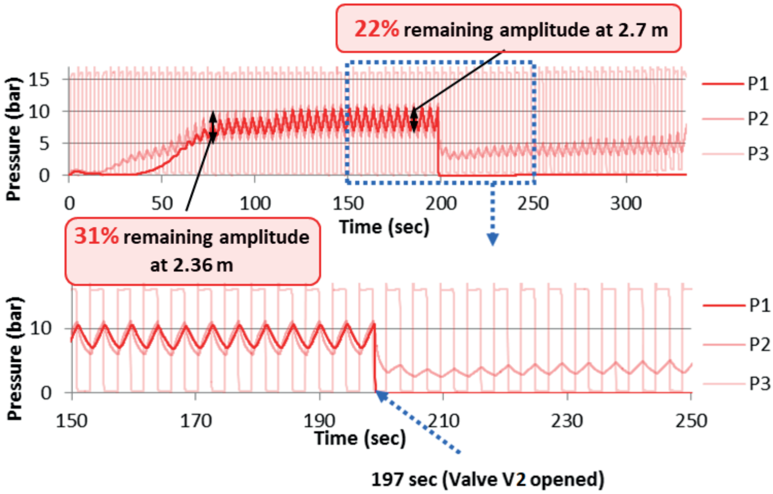

Fig. 4 Dissipation of dynamic impulses along the VALS registered by P1, P2 and P3 in test group D1 (with 2s/2s peak/rest period)

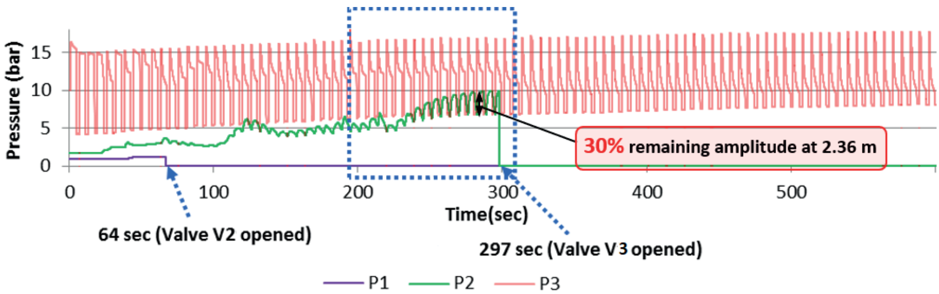

Fig. 5 Dissipation of dynamic impulses along the VALS registered by P1, P2 and P3 in test group D2 (with 1s/5.5s peak/rest period)

2.5.2 Evaluation of filtration and erosion along the VALS using min- and max-pressure envelopes

As described in section 2.4, to study the filtration and erosion phenomena along the VALS, two envelopes, i.e. the min- and the max-pressure envelopes, were further employed in this study. Those envelopes were the polylines connecting the minimum pressures and the maximum pressures obtained in consecutive cycles, registered by P1, P2, and P3, respectively (See BeFo reports 149, 181). Over these envelopes, any upward and downward trends were representative for the filtration and erosion processes, respectively.

Fig. 6 shows the results of the min- and the max pressure envelopes registered by P3 and P2 (at 0.0 m and 2.36 m) obtained in one the experiments conducted in test group D2 with 1s/5.5 s peak/rest period. The figure shows the results obtained between approximately 60-300 sec, when valve V2 was open as the outlet. The min-pressure envelope (the purple line) presented in this figure connects the minimum pressures obtained after 3.5 sec of the rest period in each cycle. As described in section 2.2, during the first 3.5 s of each rest period, since valve 1 is fully closed, VALS is completely disconnected from the grout tank (See Fig.

2). This means that in this period, no grout flow/pressure is provided from the grout tank. However, due to the pressure that has been trapped/remained inside the slot, the grout flow is continued accordingly. As a result, the first 3.5 s of the rest period in each cycle is associated with a gradual decrease in pressure. The magnitude of this pressure decrease is directly related to the variation in the opening sizes of the constrictions along the VALS, due to the filtration and erosion. In case of filtration, the opening sizes of the constrictions become smaller and as a consequent the corresponding reduction in pressure is decreased in two consecutive cycles (i.e. providing an upward trend in min-pressure envelope). On the contrary, in the case of erosion, the opening sizes of the constrictions become larger and therefore the corresponding pressure decrease is increased (i.e. providing a downward trend in min-pressure envelope). On this basis, the min-pressure envelope presented in Fig. 6 shows random filtration (upward trend) and erosion (downward trend) occurred in this time period along the entire slot (not in a certain location) that had gradually counterbalanced each other (providing horizontal trend) after 270 sec.

On the other hand, the max-pressure envelope (the blue line) presented in Fig. 6 connects the maximum pressures obtained in each cycle at 2.36 m from the slot's beginning. Due to the specific location of P2 (right before V2), the pressure registered by this pressure sensor is directly presenting the filtration and erosion phenomena occurred at the constriction with 50 μm aperture (located between P2 and V2). As seen in this figure, there are distinguishable time periods such as R1, R2, and R3 that the results show contradictory trends between the min- and the max-pressure envelopes, i.e. the purple and blue lines, respectively. During R1 and R3, when the trends obtained are upward in min-pressure envelope and downward in max-pressure envelope, it is an indication that the filtration has been mainly happening before P2. Therefore, lower pressure has been reached to P2 leading to a downward trend in max-pressure envelope in consecutive cycles. On the contrary, during R2, when the trends obtained are downward in min-pressure envelope and upward in max-pressure envelope, it is an indication that erosion has been happening before P2 allowing an upward trend in max-pressure envelope.

In addition, the same figure also shows that there are other time periods (approximately after 215 sec) in which the trends of the min- and the max- pressure envelopes are to some extent similar. In such occasions, the associated filtration and erosion has been happening mainly at the constriction with 50 μm aperture located between P2 and V2.

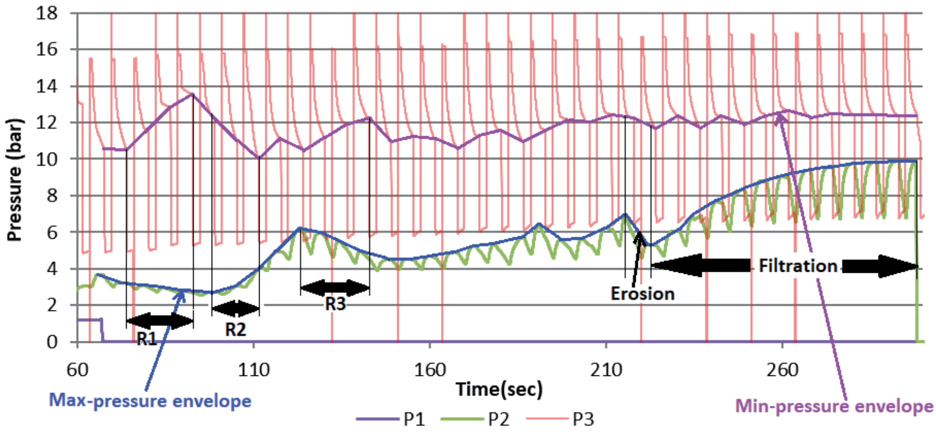

Fig. 6 Evaluation of filtration and erosion along the VALS using min- and max-pressure envelopes registered by P1, P2 and P3 in test group D2 (with 1s/5.5s peak/rest period)

2.6 Concluding remarks

Following concluding remarks can be summarized in relation to the work carried out in step one of this study:

- Using dynamic impulses with 1s/5.5s peak/rest period, the total grout volume passed through 40-70 µm apertures in VALS was improved by 10 times compared to that in the experiments conducted in static pressure condition.
- The results obtained from the experiments conducted using dynamic impulses with 2s/2s peak/rest period showed up to 31% and 22% of the initial applied amplitude remained at 2.36 and 2.7 m from the slot's beginning, respectively.
- The results obtained from the experiments conducted using dynamic impulses with 1s/5.5s peak/rest period showed up to 30% of the initial applied amplitude remained at 2.36 m from the slot's beginning.
- Even though the setup used to provide dynamic impulses in step one of this study was much better than the setup used in the previous stage of the project (reported in BeFo report 181), yet there was considerable loss of grout from the pressure release valve (valve 2) in each cycle. To fix that issue in the next step, we decided to employ a screw pump as the pressure source (instead of gas tank) using a much larger grout tank in an open system with a backflow of grout to the tank.

3. Development of dynamic grouting using screw pump (Step 2)

In step 1 of this study presented in detail in section 2, a low-frequency rectangular pressure impulse was introduced to effectively improve the grout spread in VALS in comparison to that in the experiments conducted at static pressure condition. The idea was to achieve better control on filtration by successive erosion of the produced filter cakes at the constrictions in consecutive cycles. The mechanism of improvement as suggested by Ghafar et al. (2017) was variation in the flow pattern at the constrictions due to the change in pressure and consequently the flow velocity. The maximum pressure applied during the experiments was approximately 15 bar with two selections of the peak/rest periods, i.e. 2 s/2 s and 1 s/5.5 s, using a high-pressure gas tank as the pressure source in a closed system. The results of the experiments conducted using 1 s/5.5 s peak/rest periods showed considerable improvement (up to 10 times) in the total amount of grout passed through the apertures of 40-70 μm. In addition, the dynamic impulses applied with 2s/2s peak/rest period resulted in the remaining amplitudes of as large as 31% and 22% of the initial applied amplitudes after 2.36 and 2.7 m distances from the slot's beginning, respectively. Even though the setup used to change the applied static pressure to dynamic impulses in step 1 was much more effective than that used in the previous stage (reported in BeFo report 181), yet there was some loss of grout from the pressure release valve in each cycle. Accordingly, all the experiments were eventually terminated due to the complete discharge of the grout tank, not as a result of the flow stop caused by filtration.

In order to solve the issue, in step 2, we first enlarged the grout tank to 20 l capacity. Accordingly, we needed an agitator to prevent the potential segregation/settlement of the cement particles during the grouting process. In order to use an agitator, the most frequent and the cheapest way was to change the system from a closed one to an open system (open surface grout tank). Another benefit of an open system was that we could provide a backflow of grout from the pressure release valve (valve 2 in Fig. 2) to the grout tank, instead of discharging the grout out of the system. In this way, we could deliver more grout for penetration through the VALS. This led us to change our pressure source from a gas tank to a screw pump. The main reason for selecting screw pump against piston pump was to provide a more stable pressure during each experiment without having the fluctuations that were naturally associated with the piston pump. Accordingly, the experiments were conducted using 2 s/2 s peak/rest periods at a maximum pressure of 15 bar. The goal was to investigate whether we can obtain higher improvement (in comparison to step 1) in the total amount of grout passed through the constrictions of 40 -70 μm aperture along the VALS.

3.1 Materials, mixing process, and test plan

In step 2 of the study, the experiments were conducted using a commonly used grout in the Swedish grouting industry prepared based on the same materials, recipe, and mixing process described earlier in step 1 (See section 2.3), according to the test plan presented in table 3.

Table 3, Test plan (Step 2)

Test group	Number of tests	Pressure type	Peak/rest period (sec)
C	2	Static	-
D	2	Dynamic	2 s/2 s

3.2 Test apparatus, procedure, and evaluation methods

A schematic view of the test apparatus used in step 2 of the investigation is presented in Fig. 7.

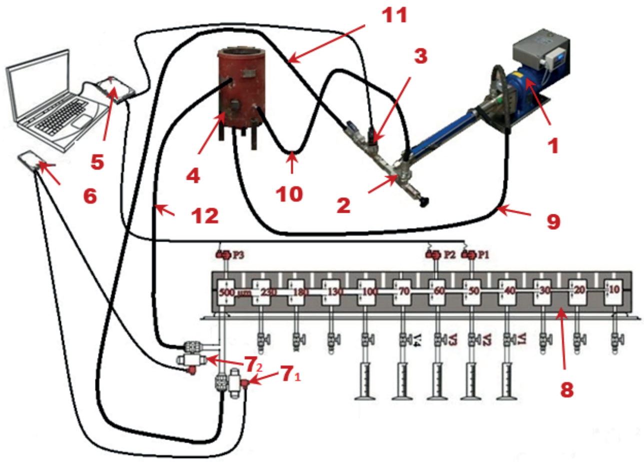

Fig. 7 Schematic view of the test apparatus used in step 2: 1) Screw pump, 2) Pressure control valve, 3) Pressure sensor, 4) Grout tank, 5) DAQ system, 6) Asymmetrical recycler timers, 7_1, 7_2) Two Two-way ball-valves with pneumatic actuators, and solenoid valves, 8) VALS, 9) Inlet from the grout tank to the pump, 10) Bypass from the pressure control valve to the grout tank, 11) Outlet from the pump to the VALS, and finally 12) Backflow from the VALS to the grout tank

As seen in figure 7, the grout tank used in step 2 was an open surface tank with 20 l capacity. An agitator was added to the tank to circulate the grouting materials inside the tank during the grouting process to prevent any potential segregation. The pressure source used was an eccentric screw dosing pump (i.e. Jessberger excenterskruvpumpar typ: JP7115.4 316TI) from Colly Flowtech AB, providing high pressure of 15 bar in the flow range of 0-2 l/min that was controlled by a frequency converter (i.e. NORD- SK 180E). The pump was connected to VALS using a high-pressure hose. The VALS itself was equipped with three pressure sensors P1-P3 located at 2.7 m, 2.36 m, and 0.0 m from the slot's beginning, respectively, to register the pressure in order to study the dissipation of the pressure impulses along the experiments. Another pressure sensor was located right after the pump's outlet to register the applied pressure during the experiments. The readings of the pressure sensors were then transformed from analogue to digital and recorded using a data acquisition-DAQ system. Furthermore, a pressure control valve that was designed to open at pressures higher than 15 bar was added to the pump's outlet to maintain the applied pressure constant. The system that was used to convert the applied static pressure to a programmable dynamic one was similar to that used in step 1 (See section 2.4). It consisted of two two-way ball-valves (i.e. 7_1 and 7_2) equipped with pneumatic actuators, and solenoid valves that were installed right before the entrance of VALS. The solenoid valves were controlled by three coupled asymmetrical recycler timers to program the duration of the peak/rest/periods.

In each experiment, the grout tank was first filled with the prepared grout right after the mixing process. In order to prevent settlement, an agitator was used to circulate the grout in tank along the experiment. By starting the pump, the grout started to circulate between the pump and the tank through a bypass loop (i.e. hoses 9 and 10, figure 7), since the valves at the entrance of the VALS (valves 7_1 and 7_2) were both closed. After stabilization of the outlet pressure of the pump at 15 bar (i.e. when readings of the pressure sensor 3 were stabilized at 15 bar), valves 7_1 and 7_2 were activated by running the recycler timers based on the predefined peak/rest period (i.e. 2 s/2 s). Accordingly, valve 7_1 was opened for 2 sec (peak period) allowing the grout flow towards the slot within hose 11, whereas valve 7_2 was yet closed. Here, it should be noted that by opening valve 7_1 and start of the grout flow through the slot, a sudden pressure drop in the system was inevitable, which was supposed to be counterbalanced by the action of the designated pressure control valve (valve 2). The purpose of the pressure control valve was to maintain the 15-bar pressure along each experiment by 0pening to release the excess pressure through the bypass loop, when the pressure was higher than 15 bar, and by closing, when the pressure was lower than that. Following that valve 7_2 was opened for 2 s (rest period) to release the internal pressure of the slot to the atmospheric pressure, shortly after valve 7_1 was completely closed. In this way, the static pressure provided by the pump was converted to a dynamic pressure with 2 s/2 s peak/rest period. The process was continued until we reached the flow stop, when each of the outlets V1-V3 were opened, respectively.

In order to investigate the dissipation of the pressure impulses along the VALS, the amplitudes of the pressure variation registered by P1–P3 at different locations were once again considered for comparison, when the pressure impulses were stabilized. Finally, the total amount of grout passed through the apertures smaller than 70 µm at dynamic pressure condition were registered and compared with that in static pressure tests. It is worth mentioning that with the setup used in step 2, there was no loss of grout out of the system in each cycle. However, we confronted with other issues that are described later in the results and discussion (Section 3.3). In this step, the VALS was water saturated before test for better pressure control. In a water saturated VALS pressure drop occurs faster when flow from the pump is closed and valve for pressure dissipation is opened.

3.3 Summary of the results and discussion

3.3.1 Improvement of the grout spread in apertures < 70 µm

A summary of the total amount of grout passed through 40-70 µm apertures at both static and dynamic pressure conditions using pump as pressure source (Step 2) are presented in Table 4. The results of the experiments conducted in step 1 (using gas tank), which have been already discussed in table 2 in section 2.5.1, are also shown in this table for further comparison.

Table 4 Improvement on grout spread in apertures < 70 µm obtained using dynamic impulses at 2s/2s & 1s/5.5s peak/rest periods compared to static pressure tests (both gas and pump driven)

Test group	Pressure sourse	Test No.	Peak/Rest period [sec]	Weight of the passed grout [g] V1 (40 µm)	V2 (50 µm)	V3 (60 µm)	V4 (70 µm)	Average (40-70) µm	Improvement of grout spread in apertures < 70 µm	Improvement of grout spread in apertures < 70 µm
C (Static)	Gas (Step 1)	1	-	84	60	0	0	102	-	
		2	-	0	0	44	16			
D2 (Dynamic)		1	1 s/5.5 s	0	120	880	-	1020	10.0	
		2	1 s/5.5 s	0	76	964	-			
C (Static)	Pump (Step 2)	1	-	-	64	290	16	491	-	
		2	-	-	60	532	20			
D (Dynamic)		1	2 s/2 s	-	206	344	0	825	1.68	8.09
		2	2 s/2 s	-	192	908	0			

As seen in table 4 (step 1), using 1 s/5.5 s dynamic impulses, the results showed approximately 10 times increase (i.e. 1020/102) in the total weight of grout passed through 40-70 µm apertures. This improvement is in comparison with the results of static pressure tests. In step 2, even though the test setup used had been designed to obtain further improvement of the grout spread in comparison to step 1 (even more than 10 times), the results obtained showed less improvement of only 1.68 times (i.e. 825/491) in the total weight of grout passed through similar apertures. Comparison of the results obtained during the static pressure tests conducted in step 2 and step 1 shows approximately 5 times improvement (i.e. 491/102) in the total weight of grout passed through the very same apertures. This is the main reason for observing less improvement (i.e. 1.68 times against 10 times) in the experiments conducted in step 2 compared to that in step 1. But what caused the increase in the total weight of passed grout during the static tests in step 2 (compared to step 1) was the fluctuation in pressure that had happened during those experiments. As described earlier, the pressure control valve that had been designed at the pump's outlet was supposed to maintain the pressure along the entire experiment at approximately 15 bar. Unfortunately, the valve used in the first dynamic test for this purpose could not sustain the numerous cycles applied along the experiment. The valve plug broke due to uneven accumulation of the produced filter cakes in the valve seat causing unbalanced pressure applied to the valve plug during relatively quick opening/closing of the valve in consecutive cycles. The defect was detected visually right after finishing the first test. Hence, we replaced the pressure control valve with a regular two-way ball-valve to manually set the pressure only at the beginning of the experiments. Consequently, all the other experiments (i.e. the second dynamic test and both static tests) were conducted using the new regular valve. This, however, was not enough and the pressure could not be exactly maintained at 15 bar along the experiments due to continuous filtration and erosion of the cement particles. Therefore, during the static pressure tests conducted in step 2, the constant pressure applied was accompanied with some sort of uncontrolled fluctuations (i.e. dynamic impulses). This might explain the reason that in the static pressure tests conducted in step 2 the results showed approximately 5 times improvement in the total amount of grout passed through apertures < 70 μm (compared to step 1). Accordingly, if the results obtained from the dynamic tests conducted in step 2 are compared with the results of some ideal static tests such as the ones conducted in step 1, the improvement in the total amount of grout passed through apertures < 70 μm would be as large as 8 times (i.e. 825/102). The fluctuations in pressure occurred along the experiments are presented and discussed later in section 3.3.2.

3.3.2 Dissipation of the pressure impulses along the VALS

Fig. 8 shows the results of the pressure-time measurement registered by P1, P2 and P3 during dynamic test 1 conducted in step 2 of the study with focus on the dissipation/variation of the dynamic impulses along the VALS. As seen in the figure, the dynamic impulses applied at the beginning of the VALS showed only a dissipation of approximately 30% (registered by P2) over the first 2.36 m of the slot with varying apertures of 230-60 μm after stabilization. The results registered by P1 shows that the dissipation of the impulses during 2.7 m length of the slot were almost similar to that occurred during 2.36 m of the slots (registered by P2). This means that the remaining amplitudes of the pressure impulses after 2.36 and 2.7 m from the slot's beginning were as large as 70% of the initial applied amplitude after stabilization. The considerable increase in the remaining amplitude of the pressure impulses at 2.36 m from the slot's beginning (from 30 to 70 %) that has been obtained in comparison of the test results of step 1 and step 2, is an indication that we were in right track and the improvement of the test setup carried out in step 2 significantly reduced the dissipation of the pressure impulses along the VALS. Unfortunately, the damage of the pressure control valve occurred during dynamic test 1 led to instability of the pressure impulses along the experiments.

As seen in Fig. 8, the maximum pressure registered during each cycle at the beginning of the slot was approximately 16 bar, when the test was started. This pressure was relatively stable without noticeable fluctuation as it should, but it gradually increased to approximately 19 bar until valve V2 was opened at 272 sec. By opening valve V2, a fluctuation began in the amplitude of the pressure impulses registered by P2 and P3 with an overall downward trend to 5 bar at the end of the test. Considering the fact that the pressure control valve, located at the pump's outlet, was supposed to keep the applied pressure constant along the experiment, the fluctuation in pressure impulses seen after 272 sec can be considered as an indication of the time that the pressure control valve was damaged. Accordingly, the variation in the amplitude of the pressure impulses registered in consecutive cycles can be a combined result of filtration and erosion along the slot as well as unsteady applied pressure due to the deficiency of the pressure control valve.

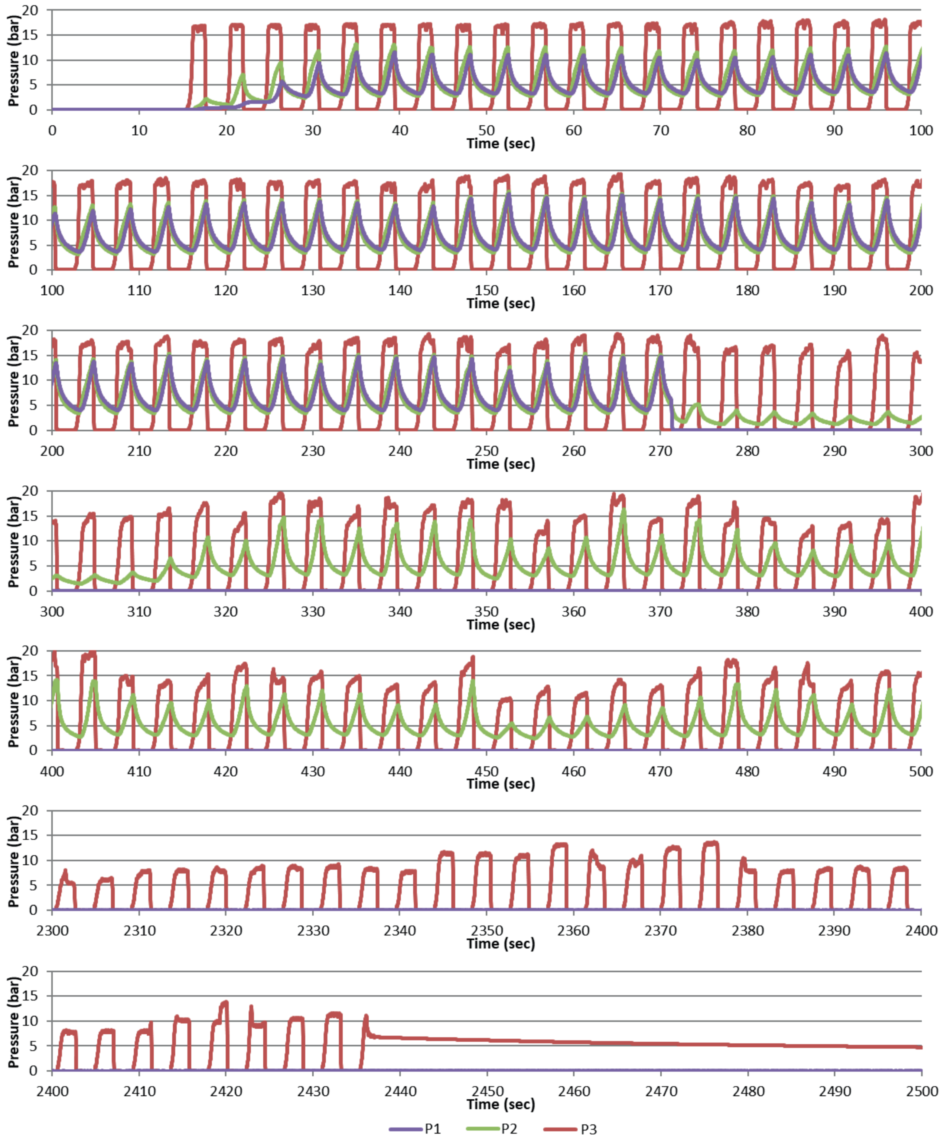

Fig. 8 Dissipation/variation of dynamic impulses along the VALS registered by P1, P2 and P3 in dynamic test 1 step 2 (pump) (with 2s/2s peak/rest period) between 0-500 sec and 2300-2500 sec

Fig. 9 shows the results of the pressure-time measurement registered by P1, P2 and P3 during dynamic test 2 conducted in step 2 of the study with focus on the dissipation/variation of the dynamic impulses along the VALS. As seen in the figure, the dynamic impulses applied at the beginning of the VALS (registered by P3) showed significant fluctuations with the maximum applied pressure varied between 8-30 bar. The variation in the initial applied pressure was continued for 312 sec. Afterwards, the maximum pressure applied in each cycle was stabilized at approximately 13 bar. As described earlier, this fluctuation in pressure was because the pressure control valve located after the pump's outlet in the test setup was damaged in dynamic test 1 and replaced with a regular valve to manually calibrate the pressure at the beginning of the slot.

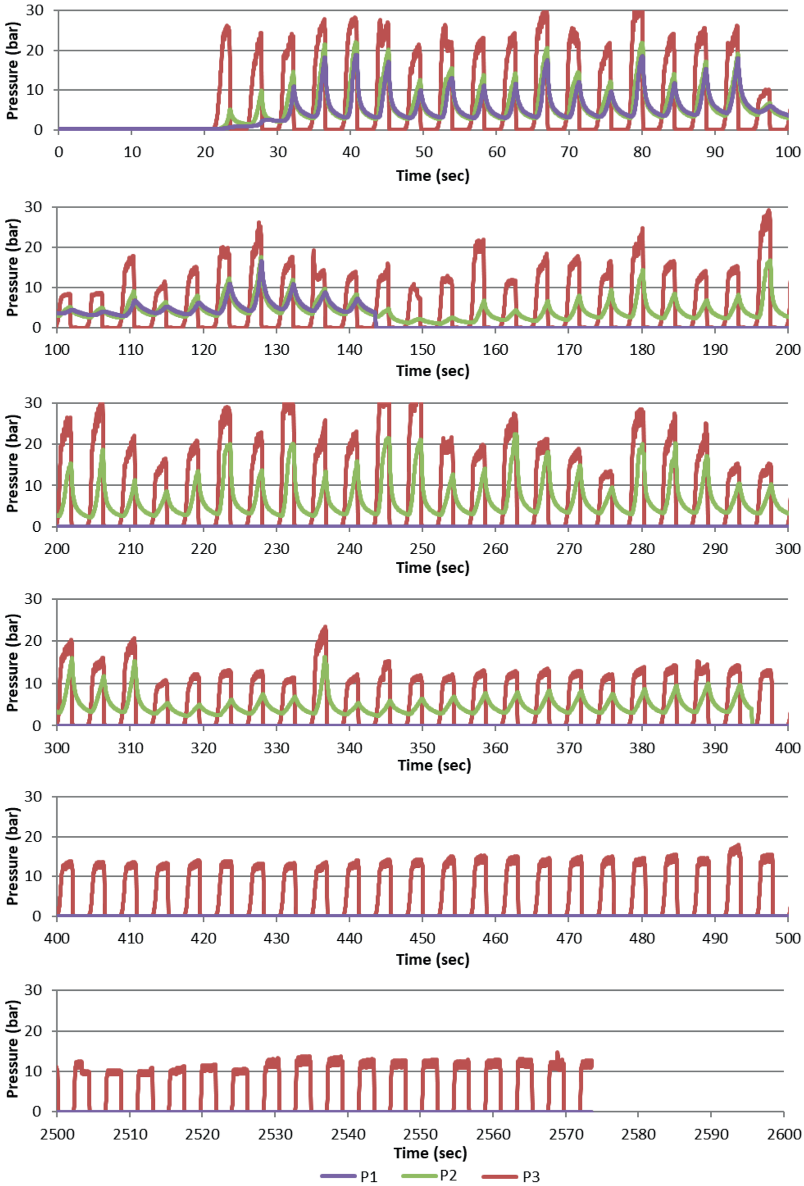

Fig. 9 Dissipation/variation of dynamic impulses along the VALS registered by P1, P2 and P3 in dynamic test 2 step 2 (pump) (with 2s/2s peak/rest period) between 0-500 sec and 2500-2575 sec

The manual calibration of the pressure at the beginning of the slot was conducted during a pre-test with water. Even though the results of the calibration during the pre-test were satisfactory, in the main test with grout, the results showed significant fluctuation in pressure. That was mainly because of the random filtration and erosion of the cement particles in the valve, which influenced the size of the valve's opening and consequently caused the fluctuation in pressure. Apparently, the formation of the filter cake in the valve became relatively stable after 312 sec and thereupon the fluctuation in pressure became lower and lower over time. It should be noticed that in this test despite considerable fluctuation in pressure registered by P3 at the beginning of the slot, yet the remaining amplitudes of the pressure impulses at 2.36 m and 2.7 m from the slot's beginning were considerable in comparison to the initial applied amplitude.

3.3.3 Fluctuation in the applied pressure during the static pressure tests

Figs. 10 and 11 show the results of the pressure-time measurements registered by P1, P2 and P3 during static tests 1 and 2 conducted in step 2 of the study. As seen, the pressures applied at the beginning of the slot in both tests (registered by P3) showed significant variations during the experiments, i.e. between 33-0 bar in static test 1 and between 40-3 bar in static test 2. These variations in pressure, as explained before, are due to the random filtration and erosion of the cement particles in the pressure control valve, which changed the size of the valve's opening along the experiment. The uncontrolled fluctuations in pressure, as suggested by Nobuto (2007), can improve the penetration and spread of grout within microfractures (See Fig. 12). Accordingly, the higher amount of grout passed through the apertures < 70 µm in the static tests conducted in step 2 compared to step 1 would be directly related to the corresponding variation in pressure.

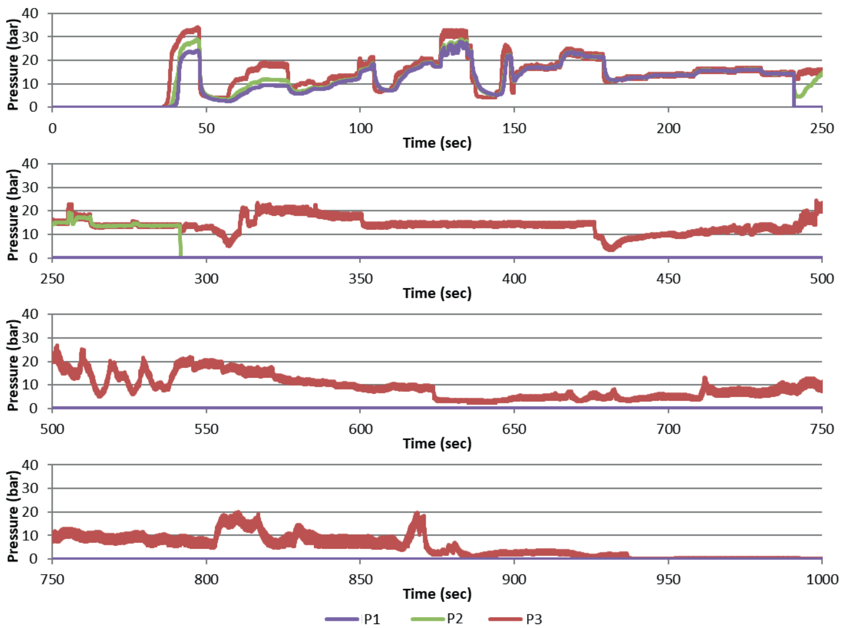

Fig. 10 Variation in pressure along the VALS registered by P1, P2 and P3 in static test 1 between 0-940 sec

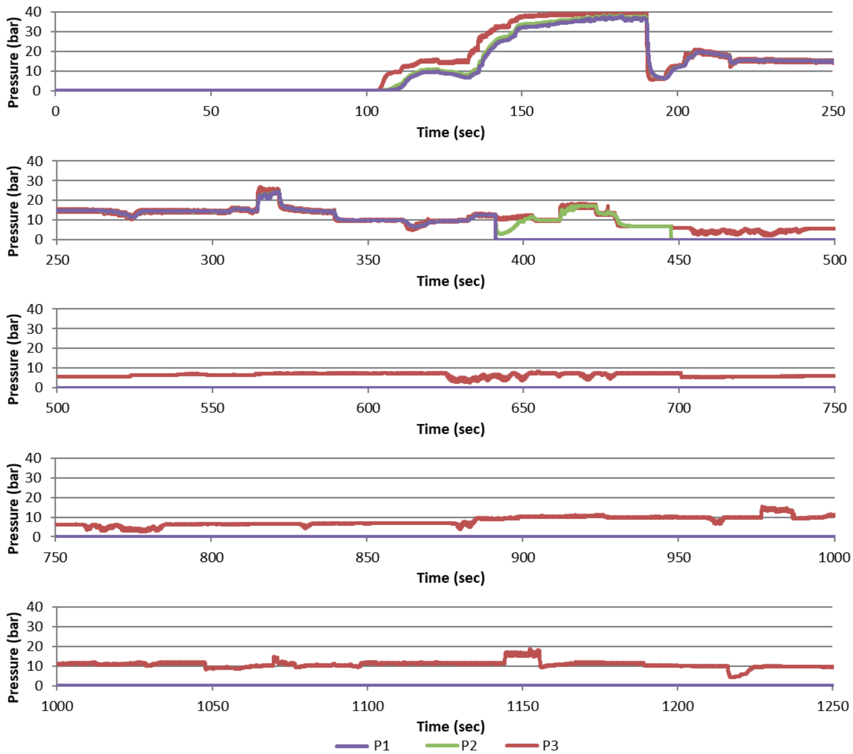

Fig. 11 Variation in pressure along the VALS registered by P1, P2 and P3 in static test 1 between 0-1250 sec

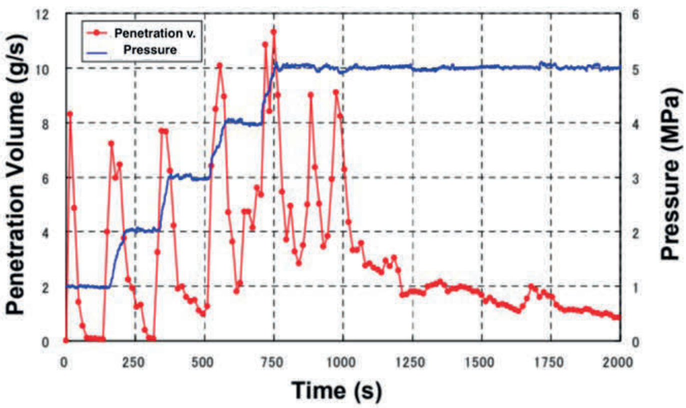

Fig. 12 Penetration volume against time with increasing pressure from 10 to 50 bar (Nobuto 2007)

3.4 Concluding remarks

The valuable outcomes of the work carried out in step 2 of this investigation can be summarized as follows:

- By applying dynamic impulses with 2s/2s peak/rest period using pump as pressure source, the total amount of grout passed through 40-70 µm apertures in VALS was improved by only 1.68 times compared to the results of the static tests. Despite that the setup used in step 2 was to further improve the grout penetration in comparison to step 1, the results showed less improvement. The main reason for that was probably the significant improvement (approximately 5 times) in the total amount of passed grout during the static tests conducted in step 2 compared to step 1. That was most probably due to the considerable uncontrolled fluctuation in pressure occurred during the static tests conducted in step 2, because of the failure of the pressure control valve. However, by comparing the results of the dynamic tests of step 2 with the static tests of step 1 (reference static tests with no fluctuation in pressure) the improvement in the total amount of passed grout was approximately 8 times.
- In comparison of the results of step 2 and 1, the remaining amplitude of the pressure impulses showed a considerable increase, i.e. from 30 to 70% of the initial applied amplitude after 2.36 m from the slot's beginning. This shows considerable reduction of the dissipation of the pressure impulses along the VALS, which was obtained by improving the test setup in step 2 in comparison to step 1 and saturating the VALS .
- Even though the setup used in step 2 was much better than that in step 1, the failure of the pressure control valve occurred during the first dynamic test in step 2 caused sever instability in the pressure applied later during the static tests. This influenced/reduced the efficiency of the system noticeably. To solve this issue in the next step, instead of a pressure control valve, a ball-sector valve controlled by an actuator, a PID control unit, and an extra pressure sensor should be added to the system (a setup similar to that described in BeFo report 149).

4. Suggestion for future studies

To improve the existing grouting technology in order to increase the efficiency of rock grouting, our suggestion for future work is further development and implementation of dynamic grouting in the field-scale. The proposed project is a supplementary investigation to maximize the efficiency of the new technique and adapt our lab-scale knowledge, obtained from the previous stages, to the field application. The aim is to demonstrate the associated economic, environmental, and sustainability advantages of the new technique to the stakeholders. It is also to introduce the method as a better alternative especially in projects with higher sealing demands such as in nuclear/toxic waste repositories to build a safer environment for the future generations. Accordingly, a distributer unit is first developed and tested in the lab to change the static pressure of a regular grouting pump to a programmable dynamic pressure. It also supplies multiple boreholes in sequence in order to improve the grout spread and reduce the grouting time simultaneously. The efficiency of the developed technique can be then demonstrated in Äspö hard rock laboratory.

5. References

Banfill, P.F.G. 2006. “Rheology of Fresh Cement and Concrete.” *Rheology Review* 2006. British Society of Rheology: 61–130. doi:10.4324/9780203473290.

Borgesson, L., and L. Jansson. 1990. “Grouting of Fractures Using Oscillating Pressure.” In *International Conference on Mechanics of Jointed and Faulted Rock*: 875–82. Vienna, A. A. Balkeme, Rotterdam.

Bruce, D. A. 2013. “Contemporary Rock Drilling and Grouting Practices.” In New Zealand Society of Large Dams (NZSOLD) and the Australian National Committee on Large Dams (ANCOLD) Conference, 12 p. Rotura, New Zealand.

Bruce, D. A., and G. Dugnani. 1994. “Innovations in American Grouting Practice.” In Proceeding of International Symposium on Anchoring and Grouting Techniques, 21 p. Guangzhou, China.

Bruce, D. A. 1992. “Current Technologies in Ground Treatment and In Situ Reinforcement.” In *Proceedings, Second Interagency Symposium on Stabilization of Soils and Other Materials*, pp. 271–95. Metairie, LA.

Draganovic, A., and H. Stille. 2014. “Filtration of Cement-Based Grouts Measured Using a Long Slot.” *Tunnelling and Underground Space Technology* 43: 101–12. doi:10.1016/j.tust.2014.04.010.

Draganovic, A., and H. Stille. 2011. “Filtration and Penetrability of Cement-Based Grout: Study Performed with a Short Slot.” *Tunnelling and Underground Space Technology* 26 (4): 548–59. doi:10.1016/j.tust.2011.02.007.

Eklund, D., and H. Stille. 2008. “Penetrability due to Filtration Tendency of Cement-Based Grouts.” *Tunnelling and Underground Space Technology* 23 (4): 389–98. doi:10.1016/j.tust.2007.06.011.

Eklund, D. 2005. “Penetrability Due to Filtration Tendency of Cement Based Grouts.” *Doctoral Thesis*. Royal Institute of Technology-KTH, Stockholm, Sweden.

Eriksson, M., M. Friedrich, and C. Vorschulze. 2004. “Variations in the Rheology and Penetrability of Cement-Based Grouts - An Experimental Study.” *Cement and Concrete Research* 34 (7): 1111–19. doi:10.1016/j.cemconres.2003.11.023.

Eriksson, M, and H Stille. 2003. “A Method for Measuring and Evaluating the Penetrability of Grouts.” In *3rd International Conference on Grouting and Ground Treatment*, 1326–37. New Orleans, Louisiana, United States: ASCE. doi:10.1061/40663(2003)79.

Eriksson, M., H. Stille, and J. Andersson. 2000. “Numerical Calculations for Prediction of Grout Spread with Account for Filtration and Varying Aperture.” *Tunnelling and Underground Space Technology* 15 (4): 353–64. doi:10.1016/S0886-7798(01)00004-9.

Eriksson, M., T. Dalmalm, M. Brantberger, and H. Stille. 1999. “Separations-Och Filtrerings Stabilitet Hos Cementbaserade Injekteringsmedel (Raport 3065 in Swedish).” Royal Institute of Technology-KTH, Stockholm, Sweden.

Fransson, Å. 2008. “Grouting Design Based on Characterization of the Fractured Rock, Presentation and Demonstration of a Methodology (Technical Report R-08-127).” Swedish Nuclear Fuel and Waste Management AB (SKB), Stockholm, Sweden.

Ghafar, A.N., S. Sadrizadeh, K. Magakis, A. Draganovic, and S. Larsson. 2017b. “Varying Aperture Long Slot (VALS), a Method for Studying Grout Penetrability into Fractured Hard Rock.” *Geotechnical Testing Journal*. ASTM. 40 (5): 871–882. doi:10.1520/GTJ20160179.

Ghafar, A.N., S. Sadrizadeh, A. Draganovic, F. Johansson, U. Håkansson, and S. Larsson. 2017a. “Application of Low-Frequency Rectangular Pressure Impulse in Rock Grouting.” In *Grouting 2017: Grouting, Drilling, and Verification. ASCE Geotechnical Special Publication 288*: 104-113. doi:10. 1061/9780784480793.010.

Ghafar, A.N., A. Mentesidis, A. Draganovic, and S. Larsson. 2016. “An Experimental Approach to the Development of Dynamic Pressure to Improve Grout Spread.” *Rock Mechanics and Rock Engineering* 49 (9). Springer: 3709–3721. doi:10.1007/s00603-016-1020-2.

Gustafson, G., J. Claesson, and Å. Fransson. 2013. “Steering Parameters for Rock Grouting.”

Applied Mathematics 2013: 1–9. doi:10.1155/2013/269594.

Gustafson, G., and H. Stille. 2005. “Stop Criteria for Cement Grouting.” *Felsbau: Zeitschrift Für Geomechanik Und Ingenieurgeologie Im Bauwesen Und Bergbau* 25 (3): 62–68.

Hjertström, S. 2001. “Microcement-Pentration Versus Particle Size and Time Control.” In 4*th* *Nordic Rock Grouting Symposium, SveBeFo Rapport 55*: 61-71. Stockholm, Sweden.

Houlsby, A.C. 1990. *Construction and Design of Cement Grouting: A Guide to Grouting in Rock Foundations (Vol. 67)*. John Wiley & Sons.

Håkansson, U. 1993. “Rheology of Fresh Cement-Based Grouts.” *Doctoral Thesis,* Royal Institute of Technology-KTH, Stockholm, Sweden.

Lombardi, G. 2003. “Grouting of Rock Masses.” In 3*rd* *International Conference on Grouting and Ground Treatment*: 164–97. New Orleans, Louisiana, US: ASCE. doi:10.1061/40663(2003)6.

Mohammed, M.H., R. Pusch, and S. Knutsson. 2015. “Study of Cement-Grout Penetration into Fractures under Static and Oscillatory Conditions.” *Tunnelling and Underground Space Technology* 45: 10–19. doi:10.1016/j.tust.2014.08.003.

Mohammed, M.H., R. Pusch, S. Knutsson, and G. Hellström. 2014. “Rheological Properties of Cement-Based Grouts Determined by Different Techniques.” *Engineering* 6 (5): 217–29. doi:10.4236/eng.2014.65026.

Müller, R., and D. A. Bruce. 2000. “Equipment for Cement Grouting: An Overview.” In Proceeding of Advances in Grouting and Ground Modification, pp. 155–72. ASCE. doi:10.1061/40516(292)11.

Müller, R., and A. G. Häny. 2000. “Contemporary Grouting Equipment.” In Proceeding of the CUC Course, Waterproofing of Tunnels. Switzerland.

Nobuto, J., M. Nishigaki, S. Mikake, S. Kobayashi, and T. Sato. 2008. “Prevention of Clogging Phenomenon with High-Grouting Pressure.” *Doboku Gakkai Ronbunshuu C.* 64 (4): 813–832 (in Japanese with English abstract). doi:10.2208/jscejc.64.813.

Nobuto, J. 2007. “High Pressure Clogging Test with Japanese Micro Cement.” Shimizu Corporation, Royal Institute of Technology-KTH, Stockholm, Sweden.

Pusch, R., S. Knutsson, G. Ramqvist, M.H. Mohammed, and A. Pourbakhtiar. 2012. “Can Sealing of Rock Hosting a Repository for Highly Radioactive Waste Be Relied on ?” *Natural Science* 4 (Special): 895–905. doi:10.4236/ns.2012.431117.

Pusch, R., M. Erlström, and L. Börgesson. 1985. “Sealing of Rock Fractures A Survey of Potentially Useful Methods and Substances (Technical Report 85-17).” Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, Sweden.

Karol, R.H. 2003. *Chemical Grouting and Soil Stabilization, Revised and Expanded*. 3rd ed. Taylor & Francis. doi:10.1201/9780203911815.

Rafi, J.Y. 2013. “Design Approaches for Grouting of Rock Fractures; Theory and Practice (BeFo Report 124).” Rock Engineering Research Foundation-BeFo, Stockholm, Sweden.

Schwarz, L.G. 1997. *Roles of Rheology and Chemical Filtration on Injectability of Micro Fine Cement Grouts*. Northwestern University.

Stille, H. 2015. *Rock Grouting-Theories and Applications*. Rock Engineering Research Foundation-BeFo, Stockholm, Sweden.

Stille, H., G. Gustafson, and L. Hässler. 2012. “Application of New Theories and Technology for Grouting of Dams and Foundations on Rock.” *Geotechnical and Geological Engineering* 30 (3): 603–24. doi:10.1007/s10706-012-9512-7.

Wakita, S., K. Aoki, Y. Mito, Y. Kurokawa, T. Yamamoto, and K. Date. 2003. “Development of Dynamic Grouting Technique for the Improvement of Low-Permeable Rock Masses.” In 1*st* *Kyoto International Symposium on Underground Environment*, 341–48. doi:10.1201/NOE9058095565.ch44.

Warner, J. 2004. *Practical Handbook of Grouting: Soil, Rock and Structures*. John Wiley & Sons.

Weaver, K. D., and D. A. Bruce. 2007. “Grout Injection Pressure.” In Dam Foundation Grouting, Revised Ed, pp. 185–92. ASCE. doi:10.1061/9780784407646.ch06.

Weaver, K.D. 1991. *Dam Foundation Grouting*. ASCE.

Weideborg, M., T. Källqvist, K.E. Ødegård, L.E. Sverdrup, and E.A. Vik. 2001. "Environmental Risk Assessment of Acrylamide and Methylolacrylamide from a Grouting Agent Used in the Tunnel Construction of Romeriksporten, Norway." *Water Research* 35 (11): 2645–52. doi:10.1016/S0043-1354(00)00550-9.

6. Appendix

The test setup employed in step 2 using a screw pump as pressure source is presented in Fig. 13.

Fig. 13 The test setup used in step 2

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