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HYDRAULIC SPLITTING

– An environment friendly rock excavation method

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Preface

This report presents results from a study regarding application of hydraulic splitting as a non-explosive method for rock excavations. The major aim of the study is to investigate the feasibility of the technology by means of theoretical studies and field tests.

The study has been carried out by a team consisting of the following members:

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The team leader has been Dr. Ulf Håkansson. Dr. Yanting Chang has performed the major parts of the theoretical analyses and MSc. Erik Ahnberg has been working with the development of the equipment and field tests.

The project had a reference group consisting of Prof. Håkan Stille /KTH, Dr. Kyösti Tuutti /Skanska AB and Dr. Manucher Hassanzageh /Vattenfall Utveckling. Their contributions for outline of the project and fruitful technical discussions are highly appreciated.

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Summary

This report presents a feasibility study of non-explosive technology for rock excavations, namely hydraulic splitting. This excavation technology is free from vibrations, toxic gases and chocking waves; therefore it is considered being environment friendly.

This technology employs a hydraulic splitter consisting of a deformable hydraulic hose in combination with half-moon shaped steel plates on each side of the hose. The splitter is inserted into a borehole and inflated by high hydraulic pressure, up to 700-1000 bar. The steel plates will produce a high directional pressure on the borehole surface and cracks are initiated in the rock. The expansion continues until the cracks have propagated and the rock breaks down. To increase the efficiency and for optimum effect a number of splitters are to be used simultaneously in boreholes with a well-arranged pattern.

Theoretical studies have been conducted to investigate the mechanisms of the hydraulic splitting process, which composes the following four stages:

1. Cracks initiation on the borehole wall will start at certain limits of the internal pressure;
2. Crack propagation occurs around the borehole and eventually the cracks will connect to the ones from the neighboring boreholes;
3. The opposite surfaces of the cracks will separate from each other and a rock beam would be formed between the boreholes. In some cases the rock beam still has ability to sustain the splitting load;
4. Final breaking-down of the rock beam occurs after a certain amount of additional deformation.

The theoretical studies were performed by using analytical solutions based on fracture mechanics as well as numerical stress analyses. The study results indicate that the equipment configuration with directional pressure has certain advantages. The studies also show that it is feasible to perform a full face tunnel excavation with the hydraulic splitting technology.

Successful field tests have been performed in various rock engineering projects and rock quarries in Sweden. One field test was also performed in an underground project in New York, USA. Some important findings from the field tests are given as follows:

- The hydraulic splitting technology significantly improves the working environment for the labors compared with blasting. Hydraulic splitting does not involve explosions, chocking waves or toxic gas emissions, so that the workers could be present at the working areas during the whole splitting process.
- It is believed that damages to the surrounding rock are very limited by using the hydraulic splitting technology. All contour holes are visible in all the field tests.
- Drilling precision is an important issue. Distance deviation of the splitting boreholes, for instance, will affected splitting efficiency negatively.

The hydraulic splitting equipment need, however, to be further developed to increase the production efficiency in term of “cubic meter excavated rock per hour”. Much time has been

used for handling the splitters during some of the field tests. It would be desirable that an automated system is employed, where mechanical arms handle the splitters and a control unit manages the splitting process.

The study results presented in this report suggest that the hydraulic splitting technology has pronounced industrial potentials in rock engineering applications. It is recommended to conduct additional research works and equipment development to achieve a more effective, robust and flexible rock excavation technology.

SAMMANFATTNING

I denna rapport presenteras en förstudie om en icke-explosiv bergbrytningsteknik, nämligen hydraulisk spräckning. Denna bergbrytningsteknik är fri från vibrationer, giftiga gaser och chockvågor, därför anses denna metod vara miljövänligt.

Utrustningen för hydraulisk spräckning (splitter) består av en tillplattad hydraulisk slang omgiven av halvmåne-formade stålplattor på ömse sidor av slangen. Splittren sätts i borrhål och slangen expanderas med ett vattentryck upp till 700-1000 bar vilket gör att stålplattorna trycker på berget tills sprickor uppstår i berget. Expansionen fortsätter tills slangen är helt rund och då berget mellan borrhålen är spräckt.

Teoretiska studier har utförts för att undersöka mekanismerna för spräckningsprocessen bestående av följande fyra steg:

5. Sprickinitiering i borrhålvägg;
6. Sprickspridning runt borrhål och sammanbindning med sprickor från närliggande borrhålen;
7. Separation av sprickans motsatta ytor och en ”brygga” formas mellan borrhålen. I vissa fall har berget fortfarande viss bärförmåga;
8. Slutlig nedbrytning av ”bryggan” med fortsätt spräckning.

De teoretiska studierna utförs genom analytiska lösningar enligt sprickmekanik (fracture mechanics) samt numeriska spänningsanalyser. Studierna visar att utrustningskonfigurationen med inriktad spräckningsriktning är effektivare för sprickinitiering och -spridning. Studierna visar också att det är möjligt att utföra en fullorttunnelbrytning med hydraulisk spräckningsteknik.

Framgångsrika fältförsök har gjorts på ett antal anläggningsprojekt i framförallt Stockholmsområdet men även i New York. Nedan är några viktiga slutsatser från fälttesterna:

- Hydrauliska spräckningsteknik är arbetsmiljövänlig jämfört med sprängning. Hydraulisk spräckning avger inga explosioner, höga ljudnivåer eller giftiga gasutsläpp, så att utrymning inte behövs under spräckningsarbeten.
- Hydraulisk spräckning är skonsam för omgivande berg. Alla konturhål är synliga i alla fältförsöken.
- Ett hålavstånd på ca. 400-500 mm är tillräckligt för att erhålla en effektiv spräckning.
- För en effektiv installation av splitter är det viktigt att borra raka och rena hål.

Hydraulisk spräckningsteknik måste emellertid utvecklas ytterligare för att öka produktionseffektiviteten i termen "kubikmeter utbryta berg per timme". Mycket tid har förbrukats för att hantera splittrarna under några av fältförsöken. Det vore önskvärt att ett automatiserat system kan utvecklas, där mekaniska armar hanterar splittrarna och en styrenhet hanterar spräckningsprocessen.

Resultaten från denna studie indikerar att hydraulisk spräckningsteknik har en stor potential som en miljövänlig och effektiv bergbrytningsmetod. Det rekommenderas att utföra ytterligare forskningsarbeten och utrustningsutveckling för att uppnå högre produktivitet, pålitlighet och flexibilitet

Innehåll

1. Introduction

Blasting is often regarded as an effective and well-proven rock excavation method in jointed hard rock. However, blasting is associated with high risks for disturbances or damages of surrounding environment, especially in urban areas, in form of vibrations, emission of toxic gases and chocking waves. There have been many cases of damages associated with blasting works. While more strict environmental requirements, including disturbance to the inhabitants, have been imposed for rock excavations, blasting is still the most common excavation method in Sweden. This fact has resulted in, for instance, more complicated permit approval processes, strict requirements on protection measures and time-consuming handling of complains during blast executions.

There are mechanical rock excavation methods, such as TBM (Tunnel Boring Machine), roadheader and wire sawing. TBM:s are expensive and therefore most suitable for long tunnels. While the TBM-method lacks flexibility in tunnelling process, the machines produce low frequency ground vibrations, which might lead to uncomfortable disturbances in urban areas. Roadheaders are widely used in soft ground tunnelling, whereas the method is seldom used in Sweden due to the rock types containing high content of hard minerals, e.g. quartz. Wearing rates and consequently the replacement costs of the cutting heads are high. Wire sawing has been increasingly used in Sweden and has achieved promising results. The cut rock blocks have to, however, be blasted into smaller boulders for transportation. Experiences indicate that this method has limited efficiency.

Some other technologies have as well been used in the past, for instance, expanding cement and Darda hydraulic rock splitter. However, these technologies have low efficiency and limited robustness. At the present state, it is believed that these technologies are not suitable for large scale rock excavation works.

There have been increasing needs for development of alternative rock excavation methods which are free from explosions, hazardous vibrations and toxic gases. The methods are also expected to be flexible, efficient, robust and safe for the workers. The project described in this report is such an effort to investigate the feasibility of using hydraulic splitting as a non-explosive rock excavation method.

Hydraulic Rock Splitter used in this project is characterized by the specially designed loading device with two steel plates. The splitters are inserted into a series of boreholes in line and splitting the rock by hydraulic pressures. Field tests have been successfully performed.

In order to obtain enhanced understanding of the mechanisms of the hydraulic splitting process, theoretical studies have been conducted by using analytical formulations as well as numerical stress analyses. Field tests have also been performed to obtain practical experiences.

2. Objectives and scope of work

Hydraulic fracturing has been employed in rock engineering and petroleum industry. To increase oil inflows, the petroleum industry has used fracturing technologies to create “artificial” fracture in the rock by pressurizing the oil well. In rock engineering, hydraulic fracturing has been used as a method for rock stress measurement. Intensive studies have been performed for these applications. However, using hydraulic pressure in boreholes for splitting rock as an excavation method has not been much investigated. The major objective of this project is therefore to investigate the feasibility of the technology by theoretical studies and field tests.

The following topics are included in this project:

- To review the existing non-explosive methods for rock excavation;
- To estimate the hydraulic pressure required for splitting the rock for typical Swedish hard rocks, so that the requirements for the hydraulic equipment could be established;
- To obtain enhanced knowledge on the crack propagation between the boreholes, so that the reasonable distances between boreholes could be estimated;
- To obtain understanding on rock breaking mechanisms so that the reasonable distances between the free surface and borehole could be assessed;
- To investigate the possibility of excavating a full tunnel face with the hydraulic splitting technology;
- To discover and recommend technical issues for equipment improvement by means of field tests.

3. Review of existing non-explosive technologies

A review of the following existing non-explosive technologies has been conducted. Short summaries of the review are given in the following sub-chapters. TBM and roadheader are not included because they are of different technical characters.

- Expanding cement
- Controlled foam injection (CFI)
- Manuel splitting wedging
- Mechanical wedges
- Water stemming
- Diamond wire sawing
- Plasma blasting.

3.1. Expanding cement

Expanding cement is a powder with extreme expansive capabilities when mixed with water. With 500kg/cm3 expansive capability, expanding cement could create expansive pressure that may be higher than rock tensile strength. The expanding process takes long time up to 24 hours or more. Therefore it is believed that this method is not suitable for efficient rock excavations in large scale.

Precautions must also be taken during operations because it might cause serious injury if in contact with eyes. The cement would can shoot out from the boreholes as the temperature rises (Dexpan, 2015).

Figure 1: Rock cracked by using expanding cement, Dexpan (2015).

3.2. Controlled Foam Injection (CFI)

The Controlled Foam Injection (CFI) is described by Chapman (1999). The method is based upon the use of high-pressure foam to initiate, pressurize and propagate fracturing in rock. An injection barrel, incorporating a proprietary hole-bottom seal, is inserted into the bottom of a pre-drilled borehole. The high-pressured foam will then be rapidly delivered to the bottom of the borehole and create a controlled fracturing of the rock. To achieve complete fragmentation requires hole-bottom fracturing in combination with radial fracturing.

Initial laboratory testing on granite blocks was done with small-scale prototype. Field tests have also performed in a deep mine. However, information about excavation rates with CFI was not given by Chapman (1999).

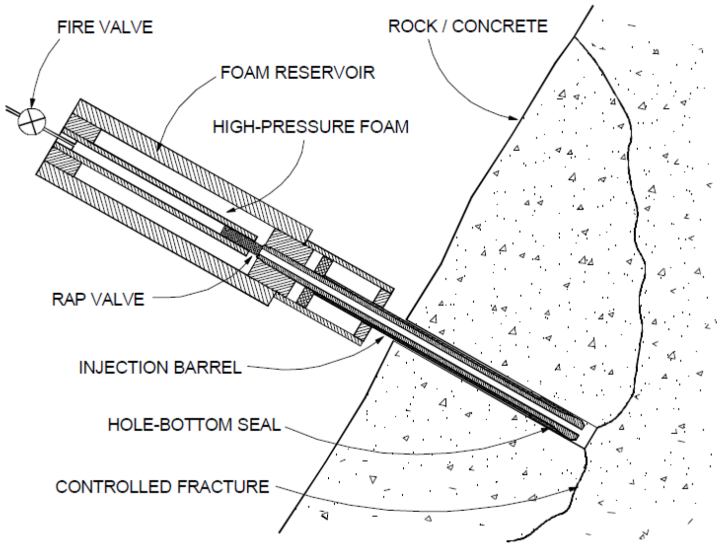


Figure 2: Controlled foam injection for rock fracturing, Chapman (1999).

3.3. Manual splitting wedging

The traditional manual rock-splitting wedges are still being used in rock quarries, mainly for extraction of minerals and natural stones. While the costs of the equipment are low, this method is labor-intensive and does not fulfil the legal requirements on working environment in Sweden. Therefor this method is not considered as a suitable method for industrial rock excavations.

Figure 3: Examples for manual wedging

3.4. Mechanical wedges

This type of rock splitters commonly consists of a central wedge and two side feathers. The central wedge is driven either mechanically or hydraulically to push the feathers outwards to produce splitting forces on the rock (see Figure 4). The available equipment on the market are

- Darda hydraulic rock splitter, Darda (2015), and
- Super wedge, Rockbreaker Tools AB (2015).

These equipment are frequently used in Sweden with favourable efficiency for small scale rock breakage in strict environments. The depth of the breakage is though limited.

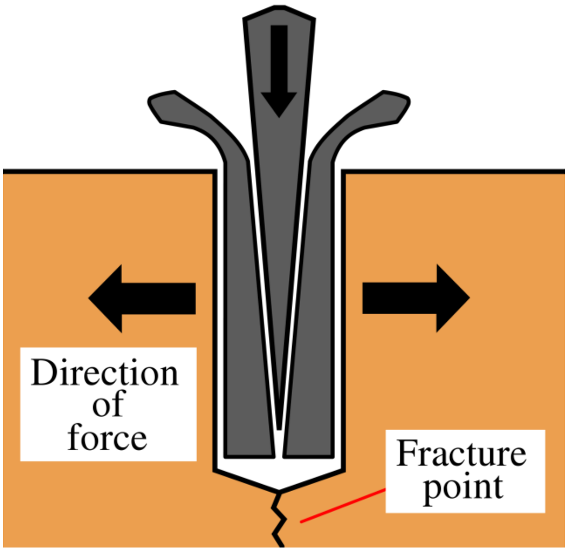


Figure 4: Principal of mechanical wedges.

3.5. Splitting Rod

Among other, splitting rods have been developed by Hwacheon HRD-TECH (2017), see Figure 5. A splitting rod is consist of a holder of diameters 80 - 95 mm with steel pistons mounted on. The pistons are pressed inwards when the rod is inserted in a borehole, then pressed outwards by hydraulic pressure to break the rock around the borehole. To increase the efficiency, a series of splitting rods are used to create interactions between the boreholes.

The equipment have been used for various applications and the results are promising (Hwacheon HRD-TECH, 2017).

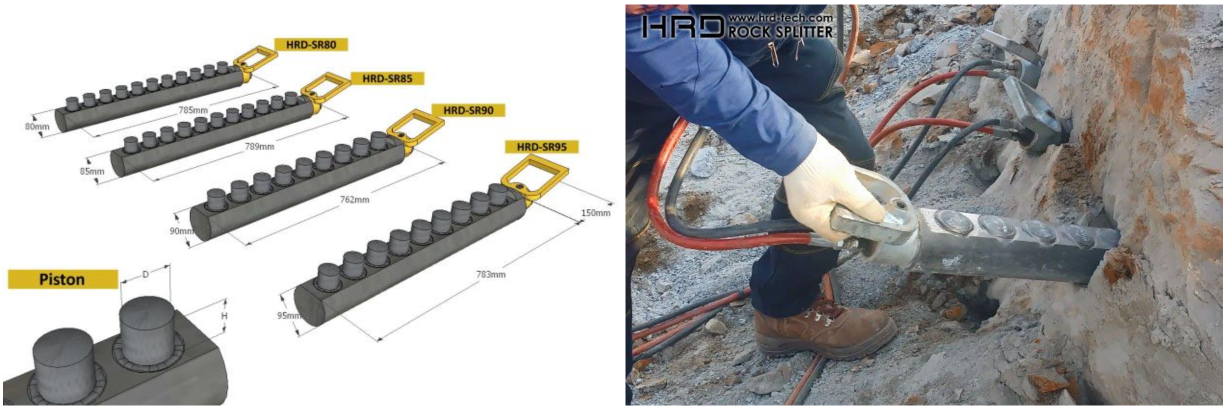


Figure 5: Splitting rods and an application example (Hwacheon HRD-TECH, 2017).

3.6. Water Stemming

In this method a small amount explosive charge is introduced into pre-drilled and water filled boreholes. Following detonation, a pressure wave is created in the surrounding water fragmenting the rock. This method could work effectively in rocks with few cracks, as any pressure leakage may affect the fragmentation negatively. It causes vibrations, though the vibration levels are lower than traditional blasting (Westerlund et al 2011). Certificate of special training is required for performing the works with this method.

3.7. Diamond wire sawing

This technology consists of a wire impregnated with diamond tips. The wire is driven by a flywheel cutting through the rock. This technology has been initially used for rock quarries for limiting damages to the valuable rock blocks. It is then introduced to rock engineering and has been successfully employed for rock excavations in strict conditions. The major drawback of the technology is the relatively low production rates. The sawed rock blocks must be also blasted into small pieces for transportation. The technology requires a relatively large working area. Therefore it is not suitable for some occasions, such as excavations in basement of existing buildings.

Figure 6: Primary cut with diamond wire

3.8. Plasma Blasting

Plasma blasting technology is patented by Noranda Technology Centre. Plasma is created by pressing electrolyte into a borehole under high pressure combined with high temperature. The plasma expands and the energy is propagated into the surrounding rock as shock waves, fragmenting of the rock without dusts and flying stones, Minde (2006) and Westerlund et al (2011). The method has been tested on rock blocks with positive results and is considered as reliable and efficient.

4. HYDRAULIC SPLITTER USED IN THIS STUDY

A new hydraulic equipment for rock splitting has been under development since 2007. The patented hydraulic splitter is characterized by a deformable hydraulic hose in combination with half-moon shaped steel plates on each side of the hose, see Figure 7. When the hose is pressurized and inflated by hydraulic pressure, up to 700 bar, the steel plates are pushed outwards applying directional pressure on the borehole wall surface. The directional pressure will then create fractures and break the rock around the borehole. When the splitting process is completed and the hydraulic pressure is released, the hydraulic splitters returns to its original shape and ready for re-use. This configuration of the splitter has been proven more effective, portable and handy to use.

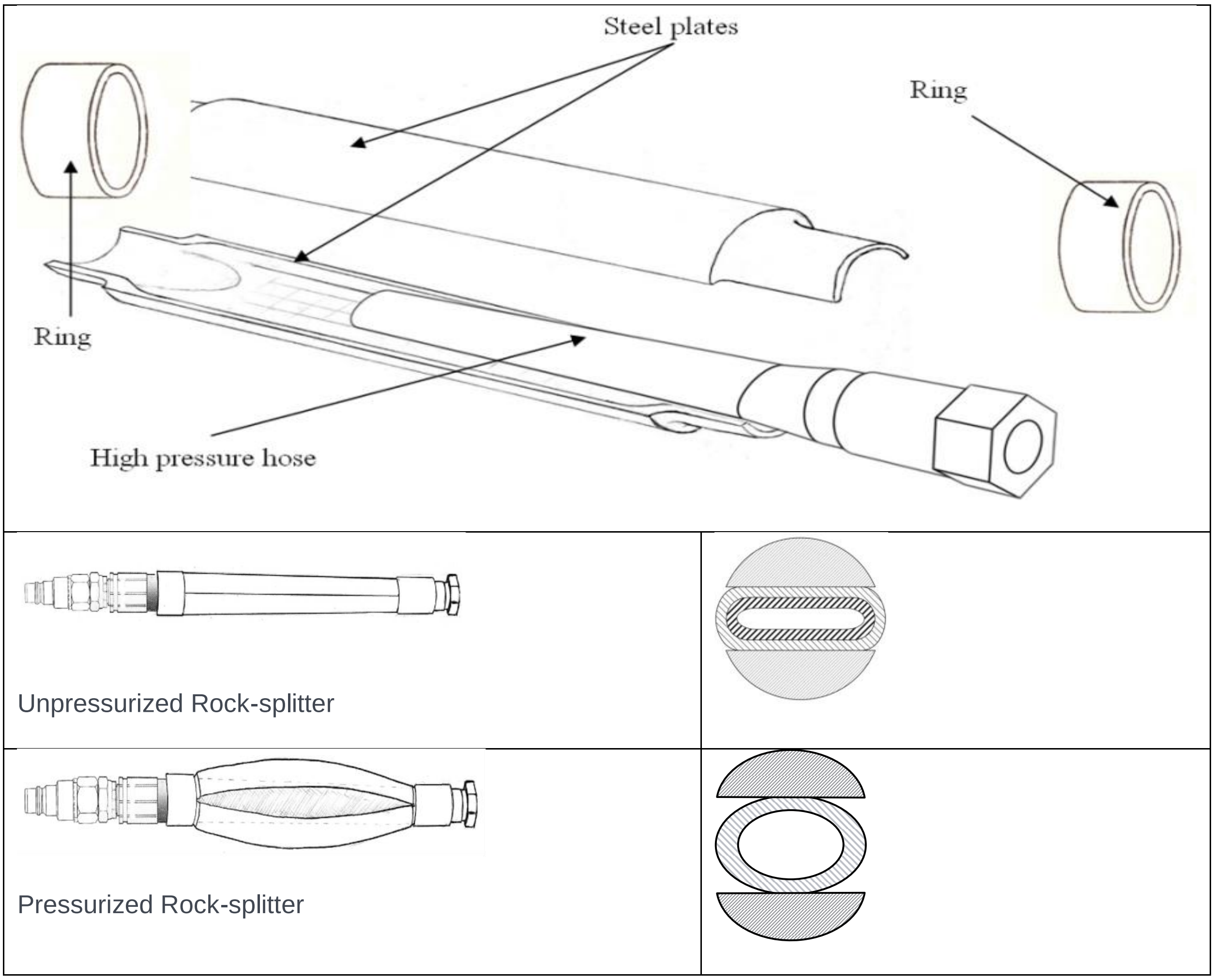


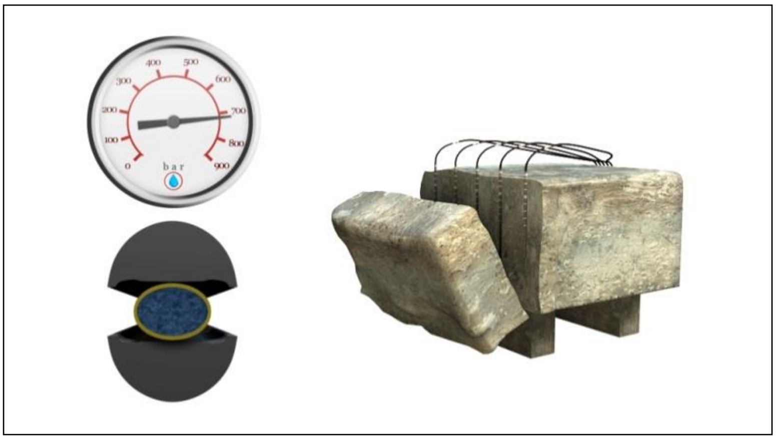
Figure 7: Hydraulic rock splitter used in this project

A short description of the operation procedure is given as follows (see Figure 8).

1. System set-up: A series of splitters are inserted into pre-drilled boreholes and are connected to a hydraulic pump. The hoses inside the splitters are in the compressed position.
2. Splitting: When hydraulic pressure is applied, the hoses will expands pushing the steel plats against the borehole wall surfaces. Cracks will then be created on the borehole walls and propagate between the boreholes until the rock is split along the boreholes.
3. When the rock is split, the pressure in the splitters is released. The hoses will be flattened and the splitters will returns to their original shape. The splitters are ready for re-use.

1. Set-up

2. Splitting



3. Ready for re-use

Figure 8: Working procedures for the hydraulic rock splitter

The hydraulic rock splitter has been continuously improved during this project. The first version of the splitter was of diameter 46 mm. The first field tests show that cracks could be created, but the cracks did not propagate far enough as wished, so that the rock hade to be broken down by a hydraulic hammer. Further investigations indicated that the major reason was the limited expansion capacity of the splitter.

The splitter was modified to have more expansion capacity. In order to provide more forces, new hose materials have been tested and shown promising results. In laboratory testing the burst pressure of the hoses are about 1100bar for 1-inch hose and 1750bar for ½ inch hose. Splitter with larger diameter was also made available for cases where more force on the borehole wall surface is required.

5. Theoretical studies

Pressurizing a borehole wall to create fractures has been used in the petroleum industry to increase oil inflows into the borehole. In rock engineering the technique has been used as a method for rock stress measurement. Fracturing mechanisms caused by an applied pressure in a borehole have been therefore intensively studied. However, interactions between multi-holes have not much investigated. The following sections will first give a summary of the related studies found in the literatures regarding the mechanisms of hydraulic fracturing in a borehole. The analyses are thenceforth made for the splitting mechanisms with multi splitting boreholes interacting with each other.

The entire process of rock splitting with a free rock surface is schematically shown in Figure 9. The process consists mainly of the following four stages:

1. Cracks initiation on the borehole wall will start at certain limits of the internal pressure;
2. Crack propagation occurs around the borehole and eventually the cracks will connect to each other;
3. The opposite walls of the cracks will separate from each other and a rock beam is formed, if the rock still has ability to sustain the splitting load;
4. Final breaking-down of the rock beam occurs after a certain amount of deformation.

Section 5.1 and 5.2 present discussions regarding the crack initiation and crack propagation, based on the theory of elasticity and the theory of fracture mechanics. Results of numerical models found in the literature concerning the influences of pre-existing geological features will be presented in section 5.3.

A simple model based on the beam theory is used in section 5.4 to evaluate the required splitting load for breaking the rock beam. Section 5.5 presents a simulation of the splitting process in a numerical model to study the interactions between the boreholes.

Stress analyses have also been carried out to study the feasibility of using hydraulic splitting as a method for tunnel excavation. Numerical models have been used to study the stress distributions in the vicinity of the tunnel face. In order to overcome the difficulties with splitting the constrained rock in the tunnel face, a configuration with an opening cut and surroundings splitting holes is proposed. Stress analysis of this configuration is performed by means of a numerical model. These are presented in section 0.

It is worth pointing out that the aim of the theoretical study of the current project is to get a preliminary understanding of the cracking mechanisms for an internal splitting pressure in boreholes. The findings of this project have suggested several subjects that are worth being further investigated to enhance the understandings of the mechanisms. Discussions of these subjects will be given in section 5.7.

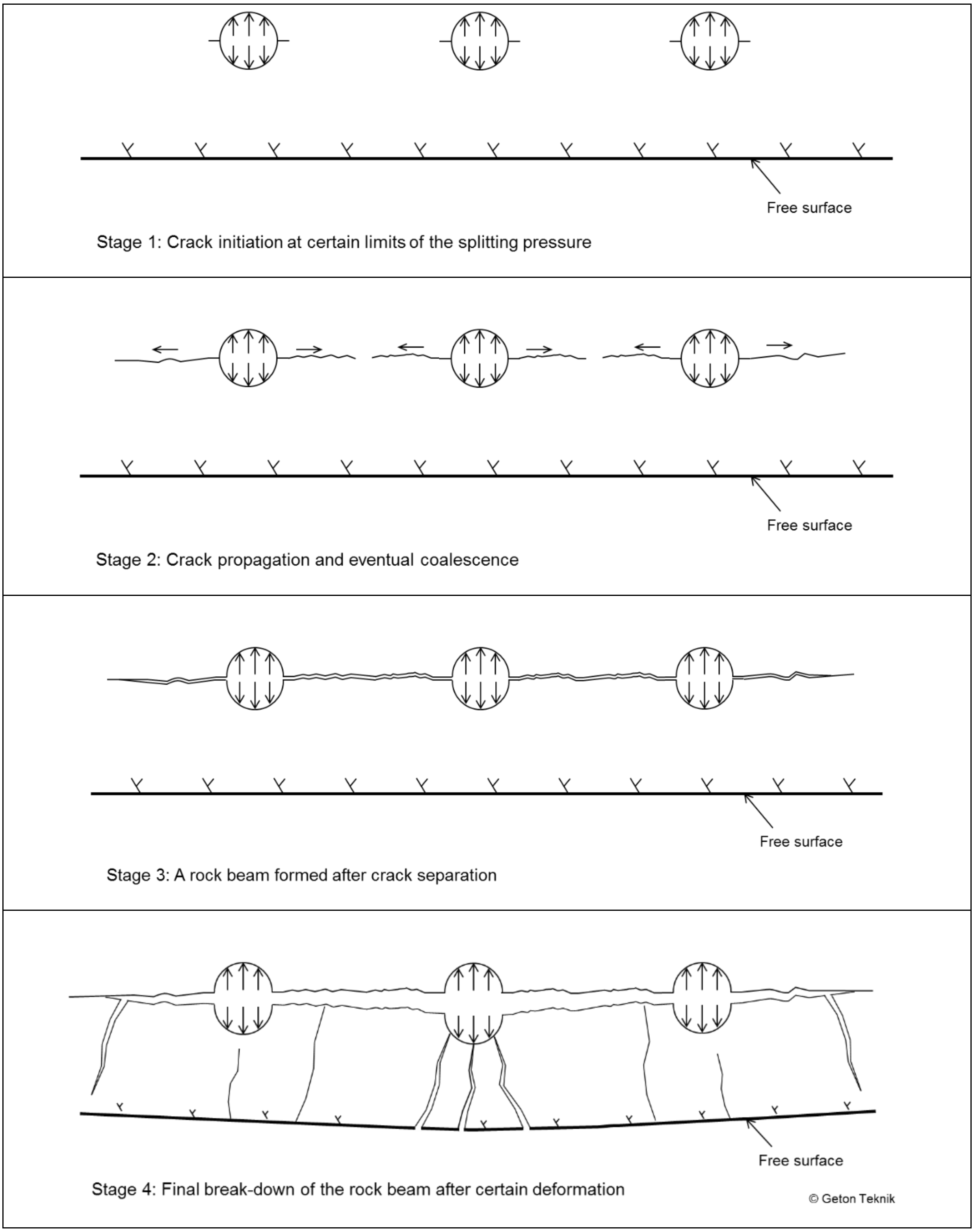


Figure 9: Process of hydraulic splitting with a free rock surface

5.1. Initiation of cracks on borehole wall

The splitting pressure required for crack initiation on the wall of a borehole is dependent on the following factors:

- Far-field stresses around the borehole;
- Stresses caused by the internal pressure inside of the borehole;
- Tensile strength of the rock;

In accordance with the theory of elasticity, the tangential stress around a circular borehole is expressed as:

$$\sigma_{\theta}^{'} = (\sigma_1 + \sigma_3) - 2 \cdot (\sigma_1 - \sigma_3) \cdot \cos 2\theta \qquad (1)$$

where σ_1 and σ_3 are the major and minor principal stress respectively of the far-field stress, θ is the angle measured from σ_1, see Figure 10. Compressive stress is defined as positive in equation (1). The least tangential stress $\sigma_{\theta}^{'}$ will be obtained when

$\theta = 0$:

$$\sigma_{\theta}^{'} = 3\sigma_3 - \sigma_1 \qquad (2)$$

This equation shows that the tangential stress at $\theta = 0$ will be in tension when $\sigma_3 < 1/3\ \sigma_1$. This is an advantageous aspect for applications of the splitting technology for rock excavations. In many situations, for instance enlarging of a tunnel section or slope excavations, rock excavations are often taking place with a free surface. In such situations, the stress normal to the free surface is usually zero or very low, which means that tensile tangential stresses already exist in the direction of σ_1 before applying the internal pressure.

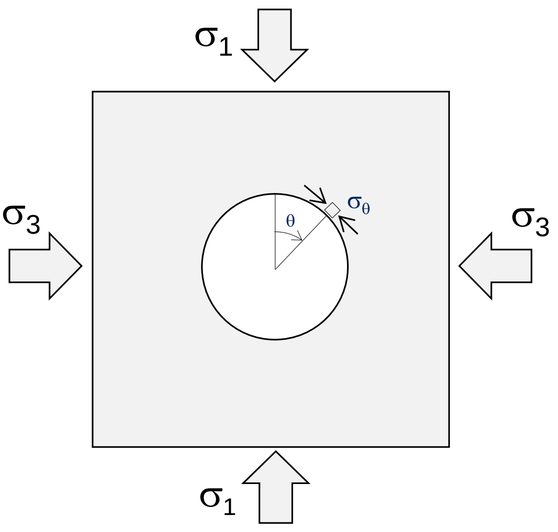
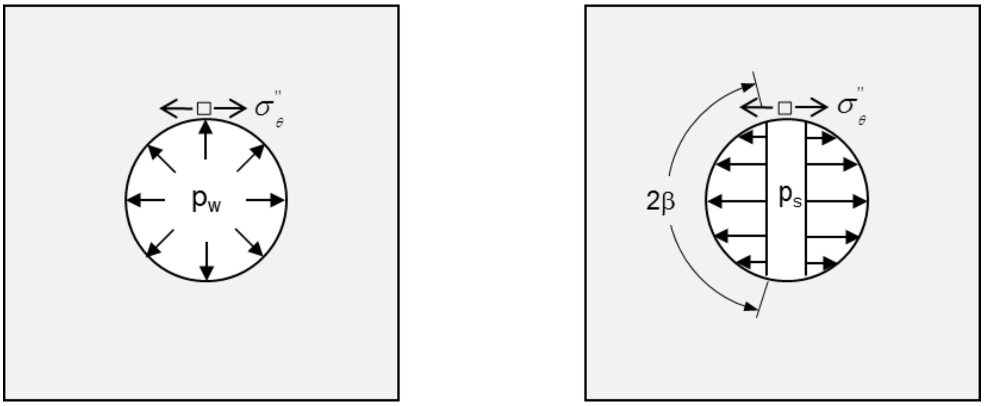


Figure 10: Stress situation surrounding a circular hole in a stressed elastic body



(a) *(b)*

Figure 11: Tangential stress caused by internal pressures inside a circular borehole

When an uniform internal pressure p_w is applied on the wall of a borehole, as shown in Figure 11 (a), the tangential stress is expressed by $\sigma''_\theta = -p_w$, in accordance with the theory of elasticity. Noting equation (2), the total tangential stress induced by σ_1 , σ_3 and p_w will thus be

$$\sigma_\theta = 3\sigma_3 - \sigma_1 - p_w \tag{3}$$

It can be seen from equation (3) that the tangential stress σ_θ will be in tension when p_w is higher than ($3\sigma_3$ - σ_1). When the tensile stress σ_θ reaches the tensile strength of the rock σ_{tc}, i.e. σ_θ = -σ_{tc}, a crack will be initiated in the borehole wall. The internal pressure required for the crack initiation will then be expressed as

$$p_w^c = 3\sigma_3 - \sigma_1 + \sigma_{tc} \tag{4}$$

For the case where an internal pressure is only partially applied on the borehole wall as shown in Figure 11 (b), no closed-form solution is available. Jaeger *et al* (1976) achieved an approximate solution of the tangential stress at the gaps:

$$\sigma''_\theta = -\frac{4 \cdot p_s \cdot \beta}{\pi} \tag{5}$$

where 2β is the arc angle over which the internal splitting pressure p_s is applied. For the splitting device used in this project, the angle 2β is approximately 135 ^{o} = 2.356 radians. Thus equation (5) will give $\sigma''_\theta = -1.5 \cdot p_s$ for the splitting device. The internal splitting pressure required for the crack initiation on the borehole wall will therefore be

$$p_s^c = 0.67 \cdot (3\sigma_3 - \sigma_1 + \sigma_{tc}) \tag{6}$$

assuming that σ_1 is oriented in the same direction of the gaps.

Recalling the equation (4) for the case of uniformly applied internal pressure, equation (6) will result in $p_s^c = 0.67 \cdot p_w^c$. This suggests that for creating the first crack on the borehole wall, the device with directional pressure requires 67% of the pressure that is required for the case with uniformly applied pressure. In other words, the splitting device with directional pressure has higher efficiency than the devices providing uniform internal pressure. Such increase in the tangential stress in the gaps is also confirmed by Charsley (2000) by numerical simulations.

The studies by Charsley (2000) show that the location for initiation of the first crack is essentially dependent on the ratio between the principal stresses $K_o = \sigma_1/\sigma_3$. When $K_o > 3$ (i.e. σ_1 is three times larger than σ_3) the initiation of the crack is most likely to start at the direction of σ_1, independent on the direction of p_s.

For applications where the minor principal stress σ_3 is of very low magnitude, e.g. enlarging of tunnel section, excavation of rock slopes or splitting of rock blocks, equation (6) can thus be written as

$$p_s^c = 0.67 \cdot (\sigma_{tc} - \sigma_1) \qquad (7)$$

Equation (7) shows that the splitting pressure required for the crack initiation is linearly dependent on the rock tensile strength. Laboratory tests have been widely conducted for determination of tensile strengths of various rocks. Table 1 presents the ranges of tested values for selected intact rocks. Based on the data of Table 1 and equation (7), Figure 12 shows the relationship between the rock tensile strength and the required splitting pressure p_s^c for crack initiation. The diagram indicates that a device with a capacity of providing directional splitting pressure of p_s^c > 15 MPa (150 bar) will cover the most of rock conditions for crack initiation where σ_3 is low.

Table 1: Tensile strength σ_{tc} for selected intact rocks (Fine Company, 2011)

Rock type		σ_{tc} (MPa)
Basalt		3 – 18
Gneiss		7 – 16
Granite		11 – 21
Limestone		3 – 5
Marble		7 – 12
Quarzite		4 – 23
Sandstone		5 – 11
Schist		5 – 12
Slate		2 – 17
Tuff		2 – 4

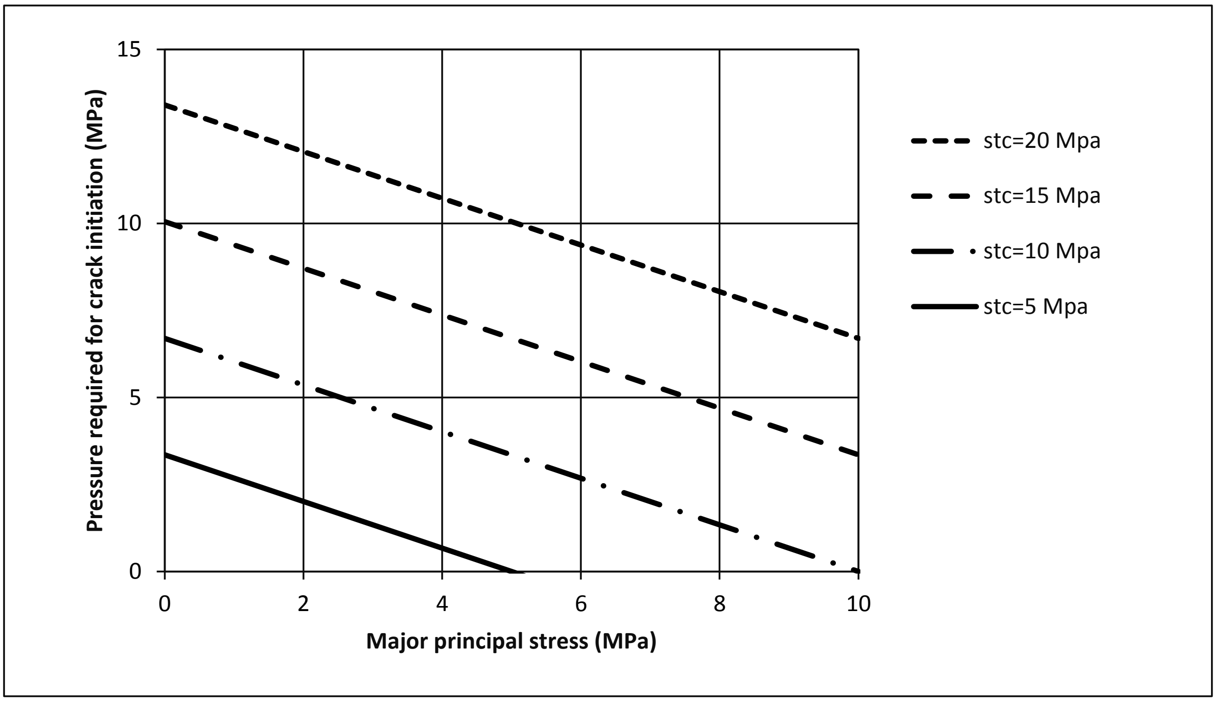


Figure 12: Relationship between rock tensile strength (stc), major principal stress σ_1 and splitting pressure p_s^c required for crack initiation (assuming $\sigma_3 = 0$)

It is worth noting that equation (6) shows that the pressure p_s^c required for crack initiation increases approximately two times of σ_3. If σ_3 is present in an application case, care must be taken for the choice of the splitting equipment.

5.2. Crack Propagation

In this section, a summary of the literature study will be given regarding crack propagations around a circular opening. Detailed study based on fracture mechanics is, however, beyond the scope of current study.

Crack propagation in rock is largely dependent on the energy required to overcome the resistance at the crack tip. The crack propagation in rocks involves a process often referred to as Fracture Process Zone (FPZ) and the process has been frequently studied as a subject of rock mechanics. This process includes extensive growth of microcracks ($1 \cdot 10^0 – 1 \cdot 10^4$ microns) and mesocracks (100 microns – 10 mm), as shown in Figure 13, prior to the main fracturing occurs. The size of the FPZ was observed to be about five to ten times the average grain size of the rock. Within the process zone the rock is in the state of de-cohesion, where microcracks coalesce to form the through-going main separation, i.e. macrocracks of several millimetres to decimetres (Backer, 2004). Non-elastic deformation within the process zone occurs caused by the stress concentrations at the fracture tip.

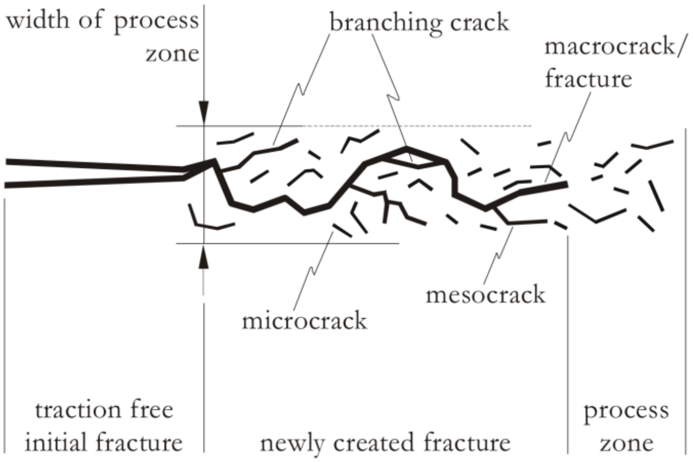


Figure 13: Fracture process zone (FPZ) consisting of micro- and mesocracks. (modified from Liu et al., 2000)

Generally there are three basic modes for crack propagation (see Figure 14):

- Mode I: Opening (tensile) mode;
- Mode II: Sliding mode; and
- Mode III: Tearing mode.

Mode I is the most relevant case for hydraulic splitting in this study. Therefore the following discussions will be focused on crack propagation in Mode I.

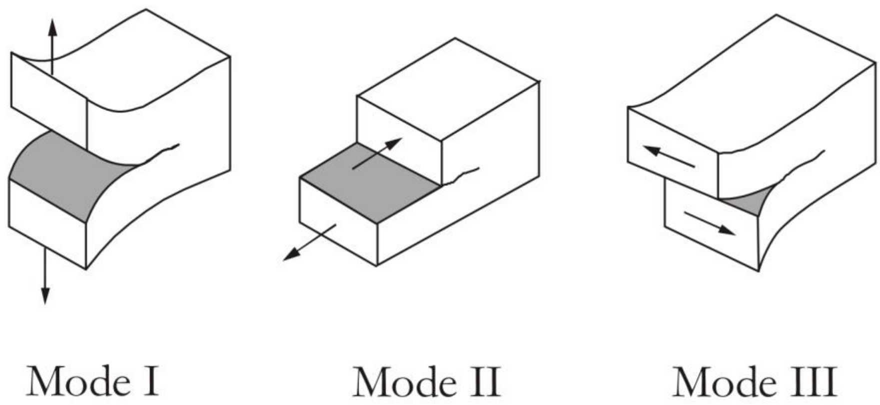


Figure 14: Basic modes of fracturing in rock (from Hudson & Harrison, 1997)

It is well recognized that the local stress at a crack tip could raise to a level several times that of the applied stress. In accordance with the theory of fracture mechanics, a parameter K_I is referred to as Stress Intensity Factor that describes the grade of stress concentration at the crack tip for mode I. This factor embodies the loading conditions, crack size and body geometry. Determination of this factor is an issue of stress analysis. As very few closed form solutions are available, the efficient and popular method is finite element analysis. Other techniques include experimental and semi-theoretical. The following is an attempt to determine the stress intensity factor K_I and the criterion for crack propagation for the case of hydraulic splitting, where a directional internal pressure is applied on the borehole wall.

In accordance with the theories of fracture mechanics, crack propagation in Mode I will occur when the stress intensity factor K_I reaches a critical value, i.e.

$$K_I = K_{IC} \tag{8}$$

This equation is the criterion for crack propagation.

It is important to note the different meanings of the two sides of the above equation. The left hand side represents the driving force of the crack, which depends on the applied loads and geometry of the components. The right hand side of the equation signifies the material's resistance to fracture, which is a material property called *fracture toughness*. Table 2 lists some typical values of the Mode I fracture toughness K_{IC} for some common rock types (Backer, 2004).

Table 2: Typical values of fracture toughness for Mode I (compiled by Backer, 2004)*

Rock type	Value [MPa m$^{1/2}$]	References
K_{IC}		
Diorite (Äspö)	3.21	Staub et al. (2003)[1]
Diorite	2.22-2.77	Bearman et al. (1989)[1]
Dolostone	0.81-2.57	Gunsallus & Kulhawy (1984)[2]
Granite	~2.0	Ingraffea (1981)[3]
	1.88	Rao et al. (2003)[1]
	0.65-2.47	e.g. Müller & Rummel (1984)[1], Ouchterlony (1988)[1], Ouchterlony & Sun (1983)[1]
Limestone	~0.8	Ingraffea (1981)[3]
	0.82-2.21	e.g. Bearman et al. (1989)[1], Guo (1990)[1], Ouchterlony & Sun (1983)[1]
P=0.1MPa	0.42	Al-Shayea et al. (2000)[5]
P=28MPa	1.57	
Marble	2.21	Rao et al. (2003)[1]
	0.46-2.25	e.g. Bearman (1999)[6], Guo (1990)[1], Müller & Rummel (1984)[1], Ouchterlony (1988)[2]
Sandstone	1.67	Rao et al. (2003)[1]
	0.67-2.56	e.g. Guo (1990)[1], Ouchter-lony (1988)[1/2], Meredith (1983)[2]
P=0.1MPa	1.08	Müller (1984)[1]
P=40MPa	2.21	
P=80MPa	2.54	

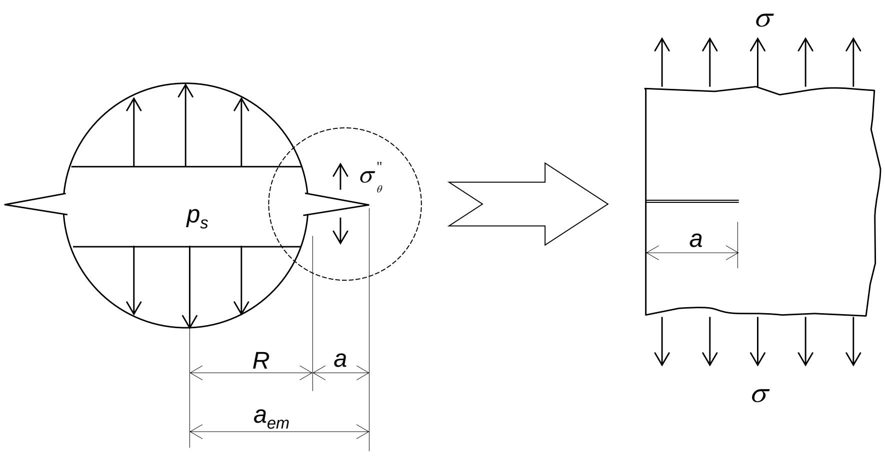
* Sources in the table can be found in Backer, 2004.

For an edge crack of length *a* in a semi-infinite half body under a tensile stress σ, see Figure 15 (b), the stress intensity factor is expressed as (Wang, 1996):

$$K_I = 1.12 \cdot \sigma \sqrt{\pi \cdot a} \tag{9}$$

Recall that the splitting device with directional pressure might produce a tangential stress with a magnitude of $\sigma_\theta^" = 1.5 \cdot p_s$ in the borehole wall. By the principle of superposition (Wang, 1996) and for a small crack length *a*, equation (9) could be used to determine the stress intensity factor for the loading condition of the splitting device with directional pressure (Figure 15-b). By substituting $\sigma = \sigma_\theta^" = 1.5 \cdot p_s$ and $a = a_{em} - R$ into equation (9), the stress intensity factor for the splitting device with directional pressure will be obtained as given by equation (10).

$$K_I = 1.68 \cdot p_s \sqrt{\pi \cdot (a_{em} - R)} \tag{10}$$



(a) *(b)*

Figure 15: A crack on in a borehole wall (a) can be simplified to an edge crack in a semi-infinite body (b)

Studies of similar cases (Wang, 1996) indicate that equation (10) is rather accurate when $a_{em} < 1.2\,R$ for engineering purposes. For longer cracks, the effects of the splitting pressure p_s will decrease at the crack tips. Consequently the value of the stress intensity factor will reduce, presumably it would approach to $K_I = p_s \sqrt{\pi \cdot a_{em}}$, when the crack becomes longer.

Additionally, it is worth pointing out that the effects of the far-field stresses σ_1 and σ_3 must be taken into account as well for a specific case. More detailed study of the stress intensity factor for long cracks with various stress situations is however beyond the scope of the current study, but is highly recommend to be conducted in further works. It could be ideal for practical applications to have diagrams as a guideline, showing relationships between the required internal pressure and crack lengths, rock types with different values of the fracture toughness as well as far-field stresses.

Numerical simulations were conducted by Backer (2000) to study the mechanisms of sleeve fracturing as a method for rock stress measurement. The configuration of the model and the loading condition is shown in Figure 16. The diameter of the hole is 60 mm. The value of fracture toughness used in the models was 2.5 MPa $m^{1/2}$. It is worth noting that the gaps are oriented 30° from the direction of the major principal stress σ_1. The value of the minor principal stress σ_3 is set to 0.5 σ_1, which is relatively high for the cases with hydraulic splitting.

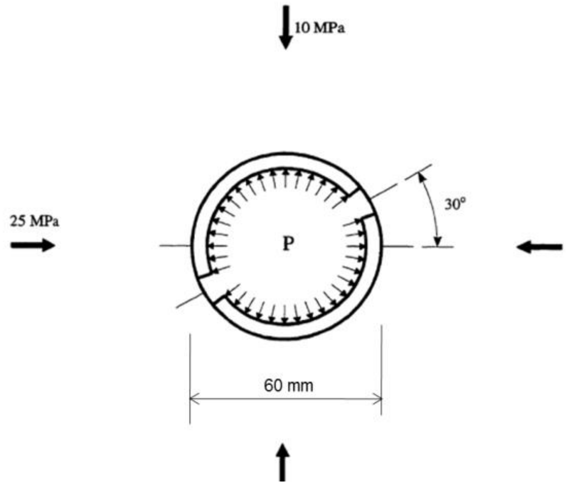


Figure 16: Configuration and loading condition of the numerical model (Backer, 2000)

The following findings are observed from the numerical simulations:

- The direction of the first crack was initiated between the gaps of the pressure.
- After the initiation of the first cracks at the internal pressure between 30-40 MPa, significant increase of the internal pressure is still required to make cracks propagate. The length of the cracks reached 50 mm at the internal pressure =70 MPa. Calculated relationship between the applied internal pressure and the radial deformation at the borehole wall is given in Figure 17. The curve indicates that the rock still has an overall semi-linear behavior even after the first crack. It is believed that the high value of σ_3 used in the simulations could have significant influences.

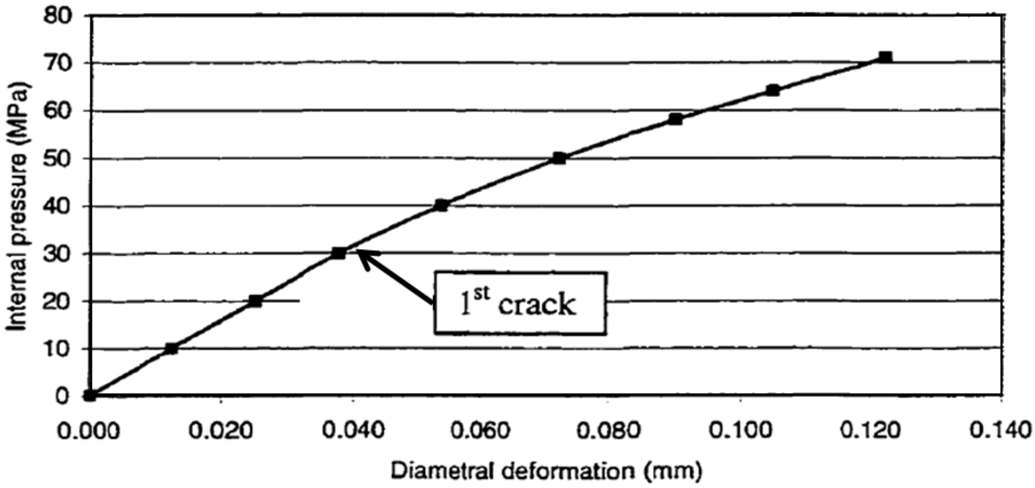


Figure 17: Calculated curve for applied internal pressure and radial deformation (Backer, 2000)

5.3. Effects of pre-existing cracks

Rock is a natural material with defects (discontinuities) in form of cracks, joints, fractures as well as faults and shear zones. It has been recognized that stresses in the rock mass are affected by these discontinuities. The pre-existing natural cracks that could have significance for hydraulic splitting might have sizes from few centimeters to meters. This section gives a brief summary of the studies found in the literatures on the effects of such pre-existing cracks.

Numerical models with one respectively two pre-existing cracks as shown in Figure 18 were conducted by Choi (2000). The horizontal far-field stress in model is set to 10 MPa and the vertical stress is zero. An uniform internal pressure is applied in the circular hole. The model material has 10 GPa for Young's modulus and 0.2 for Poisson's ratio. The models were run under the plain strain condition. Other parameters can be found in the publication.

The following observations can be made from the numerical results.

- For the both models, the direction of crack propagation caused by the internal pressure in the hole is almost parallel to the direction the applied far-field stress with slight deviation.
- For the model with two pre-existing cracks, the hydraulic cracks tend to change their directions in the vicinity of the pre-existing cracks.

It must be pointed out, however, that some important information of the modelling procedures is not given the publication, e.g. how and when the internal pressure is applied in the model. Therefore, the above observations should be taken with reservations. Nonetheless, it is well recognized that direction of crack propagation in Mode I is dominated by the direction of the major principal stress σ_1, i.e. propagation direction is predominately parallel to the direction of σ_1. If one pre-existing crack has low friction, the major principal stress σ_1 would be almost perpendicular or parallel to the pre-existing crack, which means that the new crack would approach to the pre-existing crack perpendicularly or parallel.

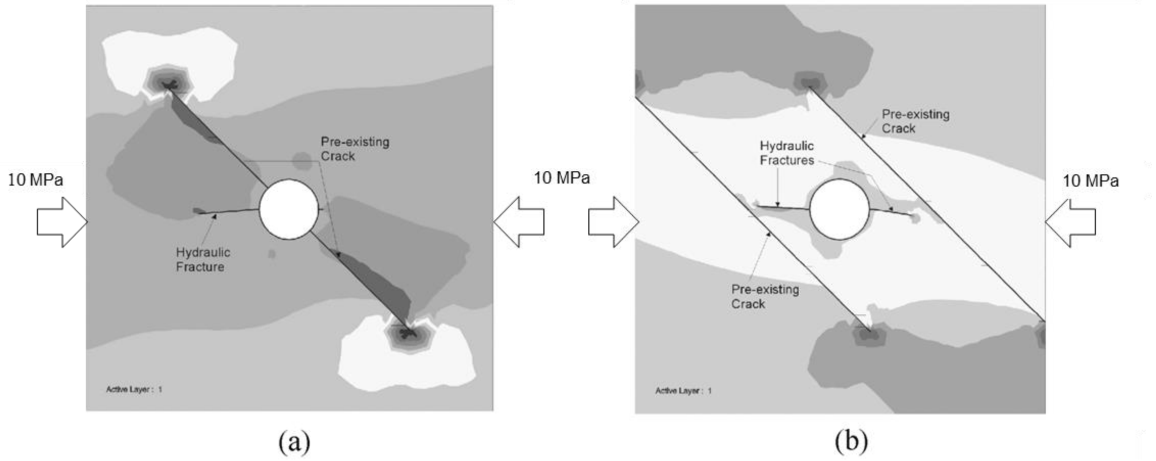


Figure 18: Numerical model for crack propagation with existing cracks

5.4. Loads required for breaking rock beam

As shown in Figure 9, a rock beam will be formed when the cracks created by the splitting have coalesced. To break down the rock beam, the applied load must overcome the bearing capacity of the beam. A simple model as shown in Figure 19 is be used to estimate the required load for breaking the rock beam.

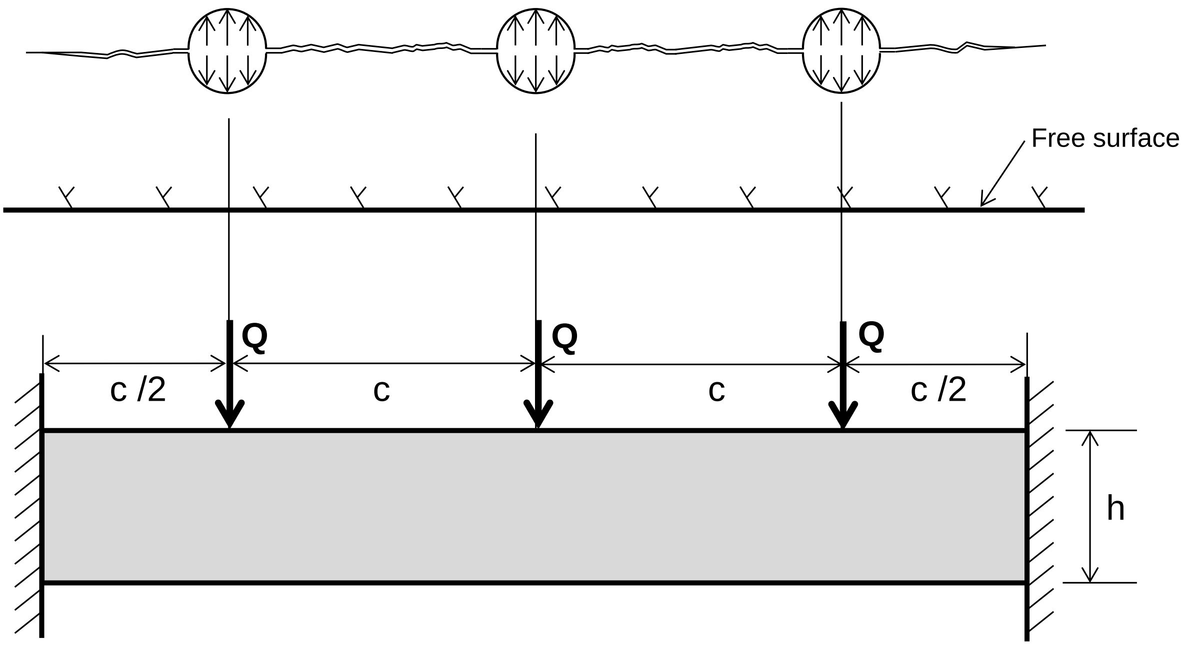


Figure 19: Model for estimating required load to break down the rock beam

According to the beam theory, the bending moments at some specific points caused by one particular load Q_i are determined by (see also Figure 20):

$$M_A^i = -\frac{Q_i \cdot a_i \cdot b_i^2}{L^2}; \quad M_1^i = \frac{2 \cdot Q_i \cdot a_i^2 \cdot b_i^2}{L^3}; \quad M_B^i = -\frac{Q_i \cdot a_i^2 \cdot b_i}{L^3} \tag{11}$$

For one specific point denoted by j , the total bending moment caused by multi loads, Q_1, Q_2 … Q_n, is expressed by

$$M_j = \sum_{i=1}^{i=n} M_j^i \quad . \tag{12}$$

where M_j^i is the bending moment caused by load Q_i at point j. The tensile stress at the specific point j induced by the total splitting loads is thus

$$\sigma_{ten}^j = \left| \frac{M_j}{W} \right| - \sigma_n \tag{13}$$

where $W = h^2/6$ and σ_n is the stress parallel to the cracking direction as shown in Figure 20.

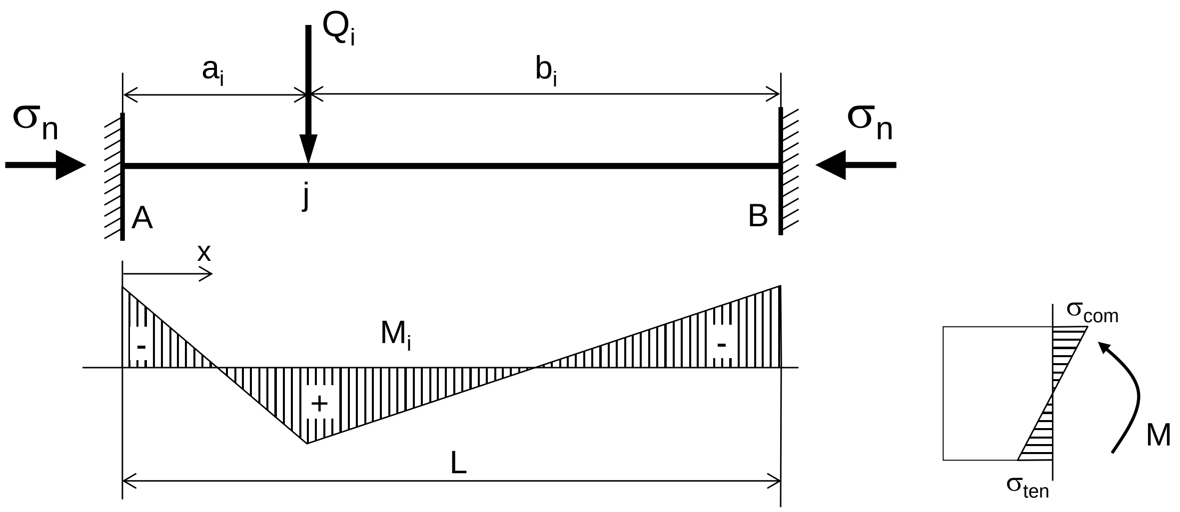


Figure 20: Bending moments caused by one particular load

It is worth noting that the stress σ_n expressed in equation (13) has the same meaning as the stress σ_1 expressed in equation (4) and (6). However, stress σ_1 expressed in equation (4) and (6) has advantageous effects for the crack initiation and propagation, whereas stress σ_n expressed in equation (13) has negative effect for breaking the rock beam.

A case study is conducted with the parameters given in Table 3. The splitting load at 3MN is equivalent to about 50 MPa pressure in a 60 mm diameter borehole.

Calculated bending moments and tensile stresses are shown in Figure 21 and Figure 22.

Table 3: Input data for the example

Number of splitting holes	3
c-c distance between splitting holes	0.4 m
Applied load, Q	3 MN (300 ton)
Beam length, L	1,2 m
Beam thickness, h	0,5 m
Normal stress, σ_n	0 MPa

It can be seen from the example that the three boreholes with 50 MPa internal pressure will create tensile stresses at 22 MPa at the ends of the beam and 14 MPa in the middle. The tensile stresses are considered as high enough for breaking a rock beam of typical Swedish rock types. The effects of the stress perpendicular to the loading direction are though not taken into account in this example.

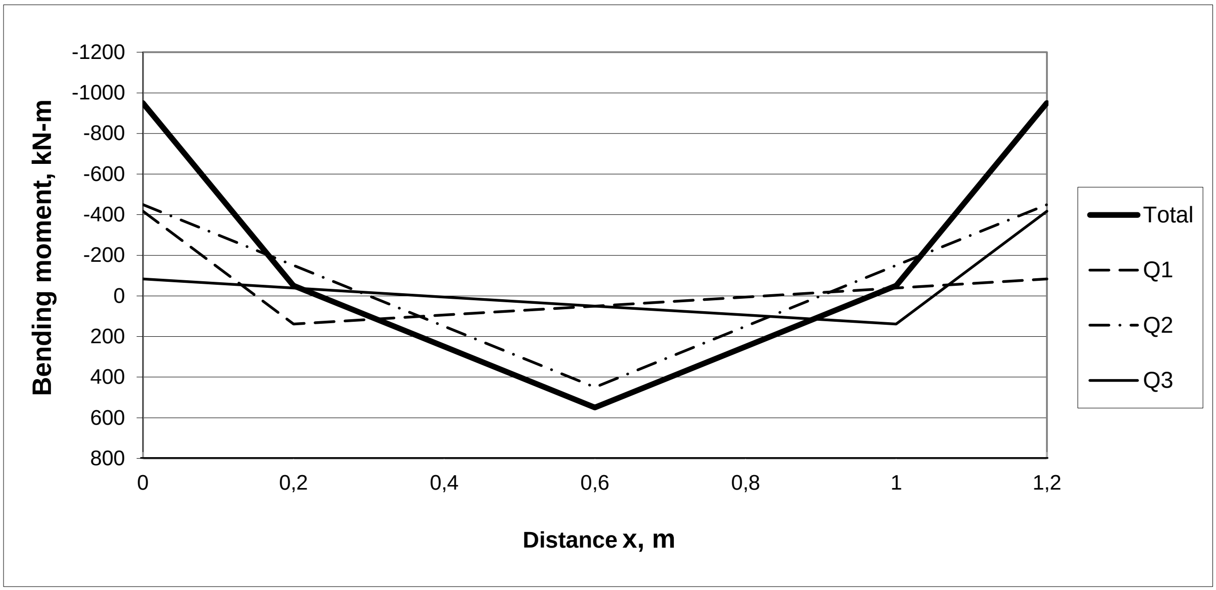


Figure 21: Calculated bending moment
(Positive value at lower side of beam, negative value at upper side of beam)

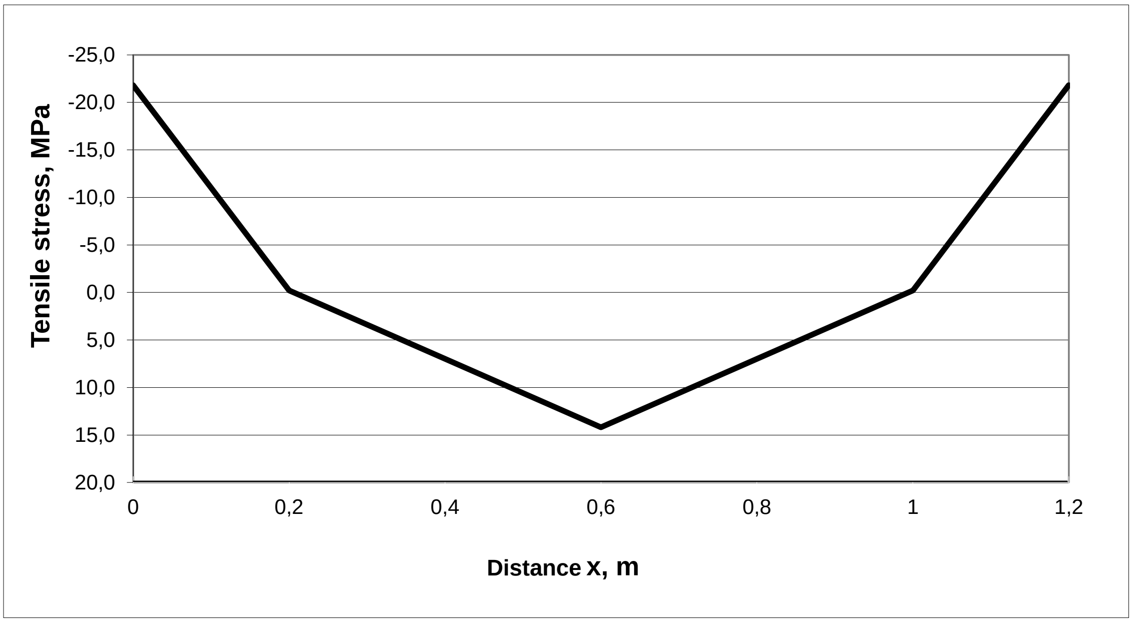


Figure 22: Calculated tensile stress
(Positive value at lower side of beam, negative value at upper side of beam)

5.5. Simulation of rock splitting with a free face

The previous sections give a review of fundamental theoretical studies on the cracking/fracturing mechanisms. This section will present a numerical simulation where three splitting holes are involved in the vicinity of a free surface. Such situations are often encountered in e.g. open pit excavation, extension of tunnel areas and slope excavations etc.

The aim of the numerical model was initially to provide judgement bases for the arrangement of the first field tests in Högalid Garage in Stockholm (se section 6.2). The purpose of the field tests was to break a rock block on the tunnel wall. The numerical model was performed in an engineering manner with the computer code FLAC, because the costs with advanced computer codes would be beyond the budget for this study.

The configuration of the model is shown in Figure 23 and the used rock properties are given in Table 4. The rock properties are equivalent to typical Stockholm granite. The diameter of the boreholes is 48 mm. There is no explicit crack imbedded in this model. The deformed mesh is used instead and updated continuously to simulate the “large deformation” problem associated with the splitting processes. The pressure inside the boreholes is applied in the horizontal direction and increases gradually during the simulation.

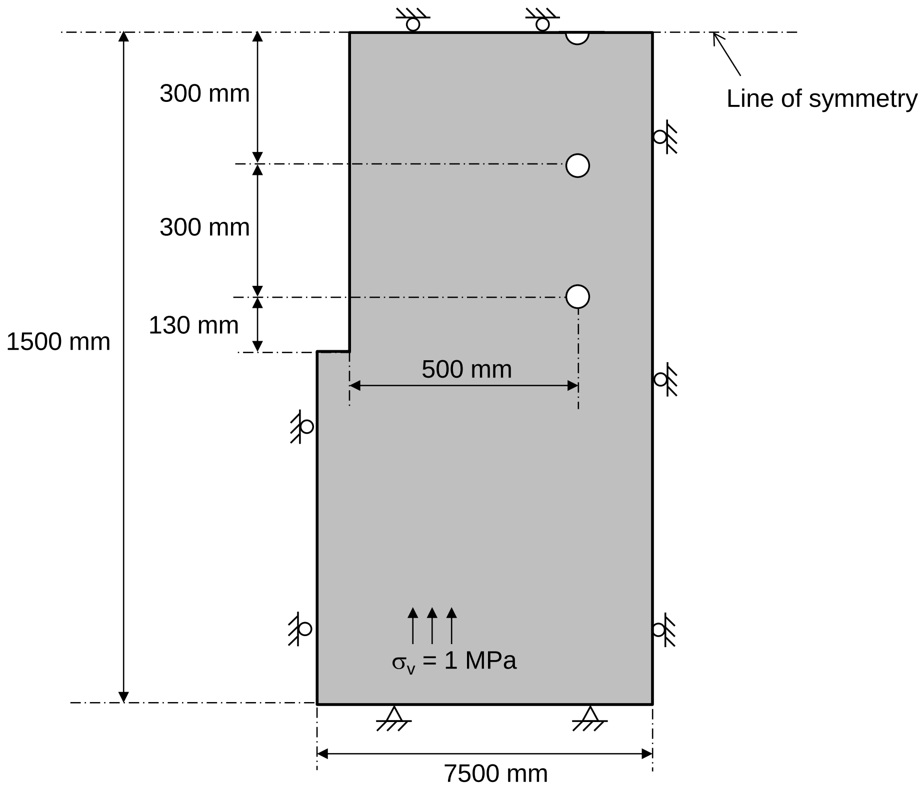


Figure 23: Model configuration for simulating hydraulic splitting with a free surface

Table 4:   Input data used in the numerical model

Young’s modulus	24 GPa
Poisson's ratio	0.25
Cohesion	3 MPa
Friction angle	45 Degrees
Tensile strength	8 MPa

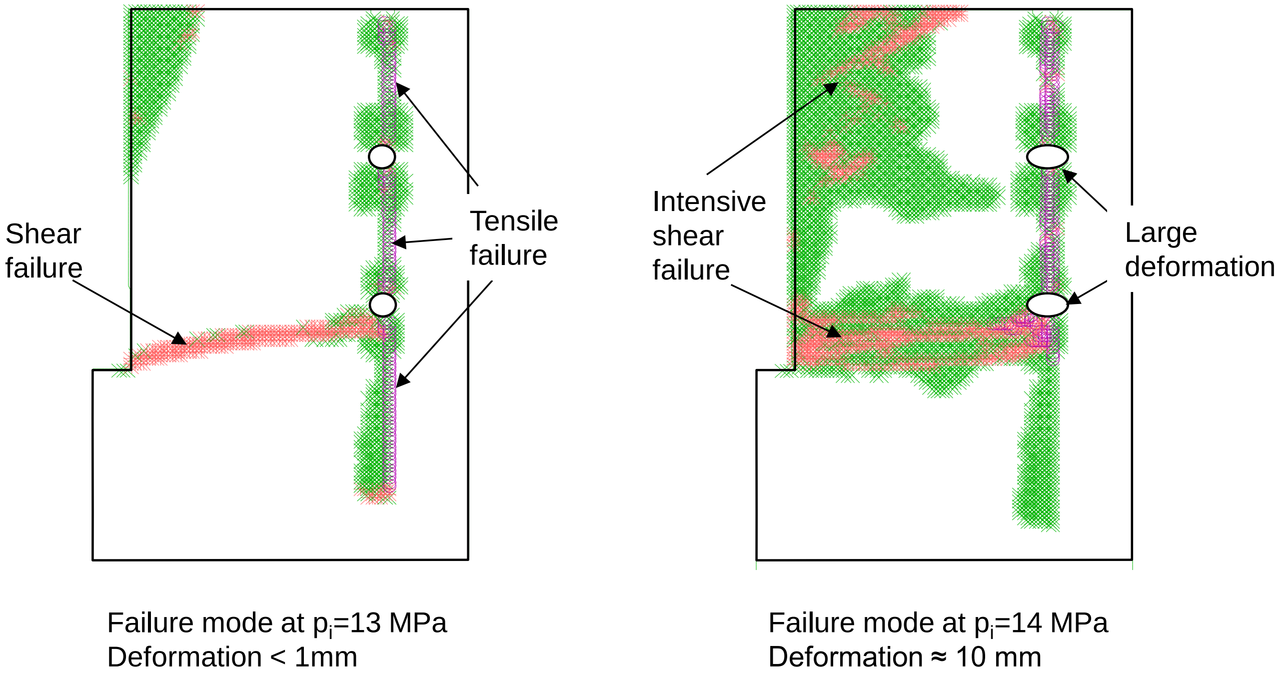


Figure 24: Simulated failure mode in the numerical model

Some of the results are shown in Figure 24. The following observations are made from the numerical simulation:

- Tensile failure (i.e tensile stress higher than tensile strength) appears entirely between the holes at a pressure level of about p_i =10 MPa and deformation level of 0.1 mm.
- At pressure level of p_i =13 MPa, shear failure occurs thoroughly at the end of the rock beam, which is a quite typical failure mode for such loading situations, similar to the tests of concrete beams. It is worth noting that the area of the tensile failure has extended quite far away from the splitting area.
- When the internal pressure reaches 14 MPa, intensive shear failure appears over almost entirely area which is intended to be excavated. The model could not reach numerical equilibrium at this stage, which can be interpreted that an overall break-down of the rock beam has been achieved by the splitting pressure.

It would be worth pointing out that the post-failure behavior of the rock in the numerical modelling is assumed being perfectly plastic. For hard rocks, the strengths would decrease significantly after the peak strength is reached. This means that the internal pressure for expanding the failure extensions would be lower than those described above. This could be a subject to be investigated in the future.

5.6. Feasibility for tunnel excavation

In the following sections, the feasibility of using hydraulic splitting as a method for tunnel excavation will be explored.

The major difference compared to the situation with a free surface is that the rock in a tunnel front is constrained by the surrounding rock. Therefore stresses around a tunnel front will be reviewed first. A proposal with bored open-cut is suggested and the feasibility of the proposal is studied by stress analysis around the open-cut.

5.6.1. Stresses in vicinity of tunnel front

Stresses in the vicinity of a tunnel front have been studied under the past decades, e.g. Chang (1994). Within the current study, a simple numerical model is performed with the aim to analyze the stresses in the tunnel front. The configuration of the model is shown in Figure 25, where the principle of axial symmetry is used in order to simulate the 3D problem with a 2D model. The rock is assumed to be linear elastic and the initial stresses σ_{xxo}=3 MPa; σ_{zzo} =3 MPa and σ_{yyo} =0 MPa are assumed. The calculated stress distributions are presented in Figure 26 and Figure 27. The results indicate that the stress concentration factor is about 1.3 for the stresses σ_{xx} and σ_{zz} in the face.

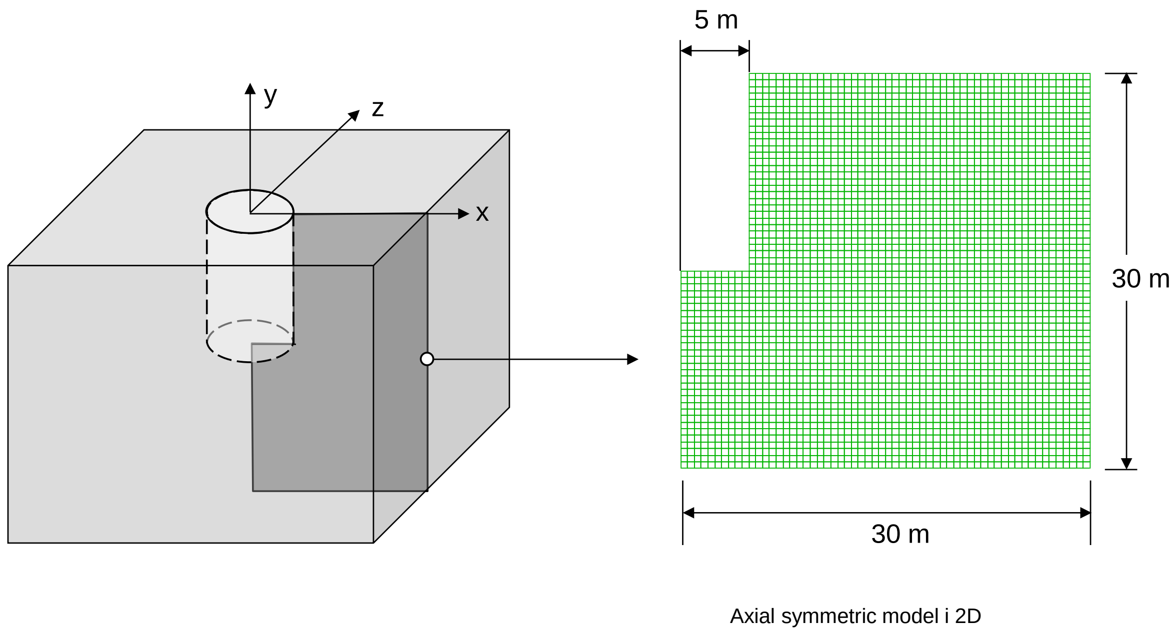


Figure 25: Numerical model for stress analyses around a tunnel face

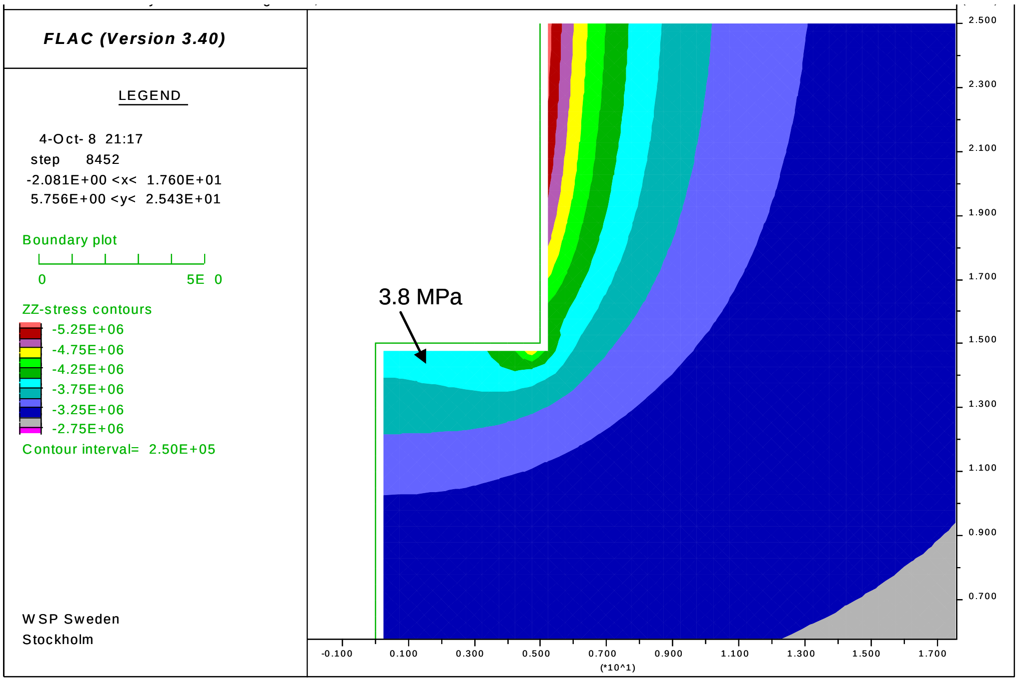


Figure 26: *Distribution of out-plane stress σ_{zz}*

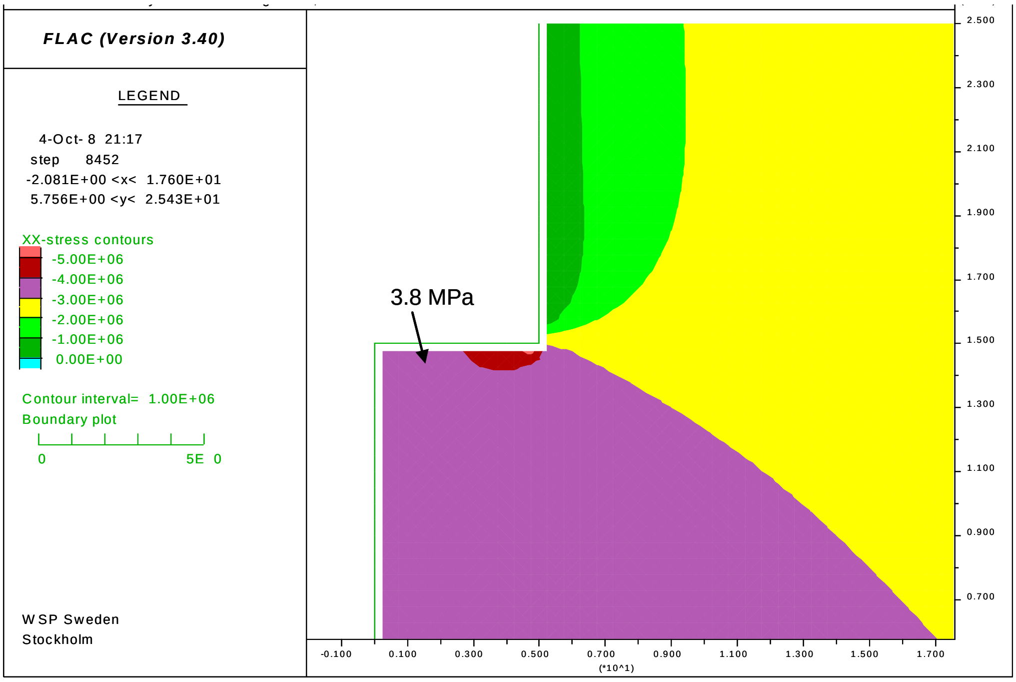


Figure 27: *Distribution of stresses σ_{xx}*

5.6.2. Hydraulic splitting in tunnel face

The previous section shows that the stresses within the tunnel face are concentrated, which increases the difficulties for splitting the constrained rock in the tunnel face. One proposed solution is to create free surfaces (open cut) by overlapped drilling of boreholes with e.g 100-300 mm in diameter, see Figure 28. To investigate the feasibility of the proposed solution, stress analyses are performed by a numerical model as shown in Figure 28. The diameter of the holes for the open cut is 300 mm and the splitting holes is 100 mm.

The material of the model is linear elastic and the stresses before the drilling of the open cut are σ_{xxo}=3 MPa and σ_{yyo} =3 MPa. Uniform internal pressures p_i are applied in all splitting holes at the same time. The calculated stress distributions at p_i =20 MPa are presented in Figure 29, Figure 30 and Figure 31. As shown in Figure 31 that tensile stresses of about 10 MPa are created between the splitting holes for p_i =20 MPa. This tensile stress is higher than the tensile strengths for typical Swedish rock types. With increased internal pressure in the splitting holes, the tensile stresses will create crack propagations between the splitting holes, as indicated in the analyses described in the previous sections.

Based on the numerical results, it is believed that the proposed solution with an open cut and surrounding splitting holes is feasible for creating a first opening in one tunnel face. The remaining part of the tunnel face can then be excavated by subsequent splitting sequences.

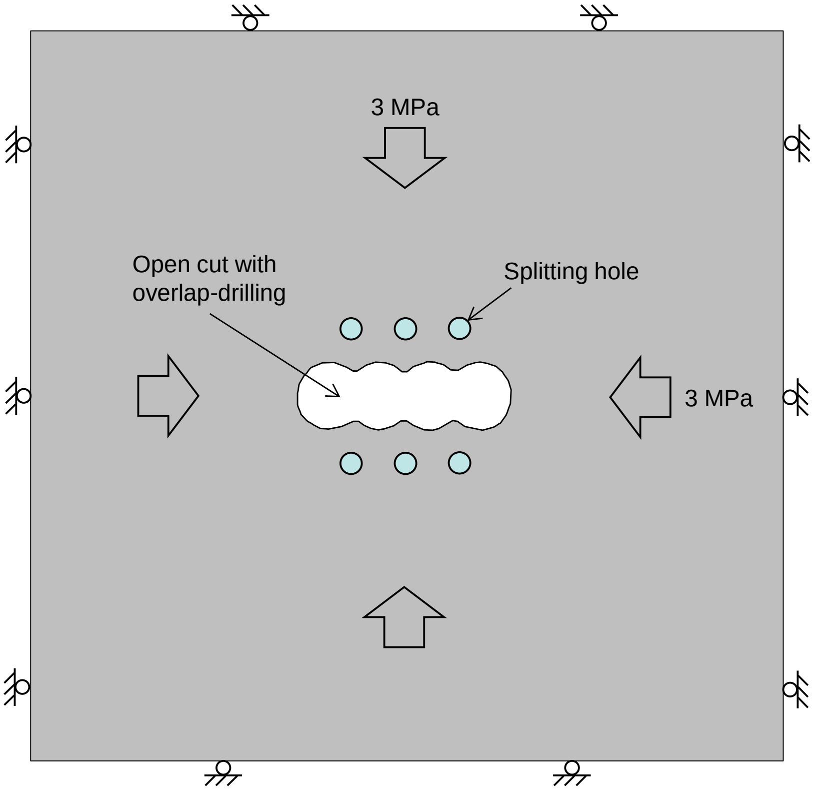


Figure 28: Configuration of open cut and numerical model for simulation

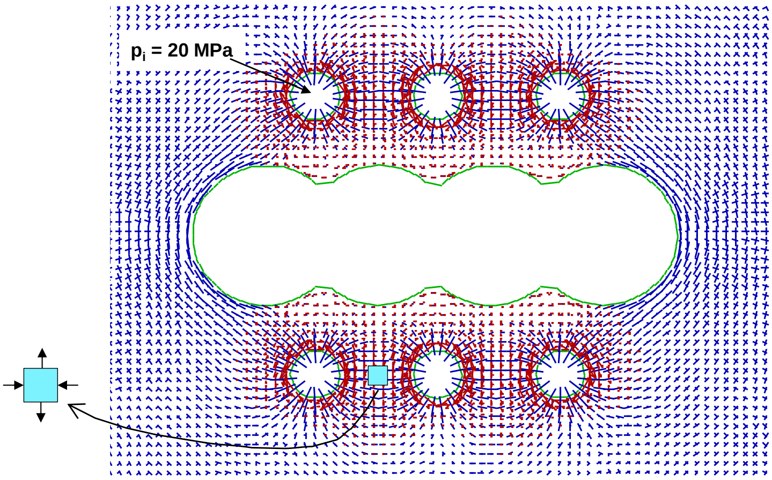


Figure 29: Stress distribution at 20 MPa pressure in the splitting holes (tensile stress in red colour)

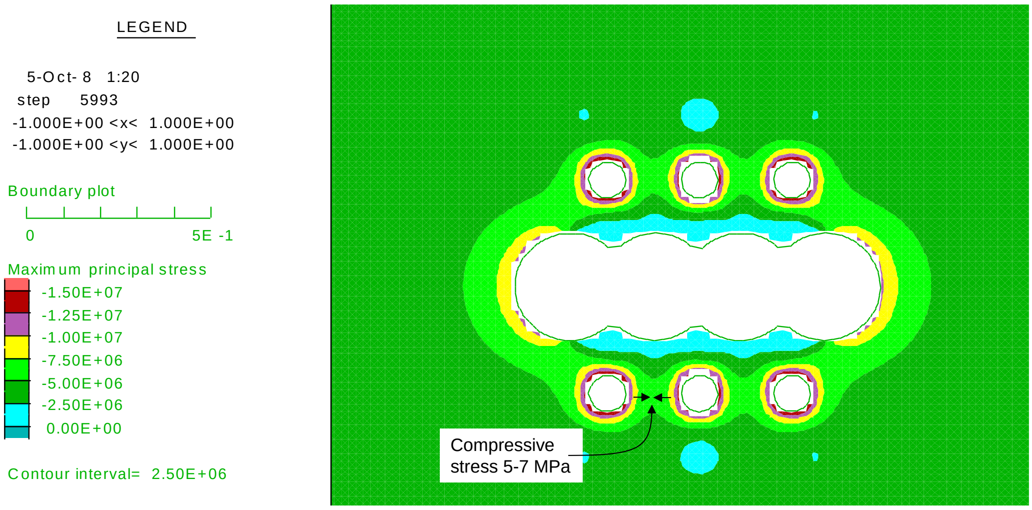


Figure 30: The major principal stress σ_1 at 20 MPa pressure in the splitting holes

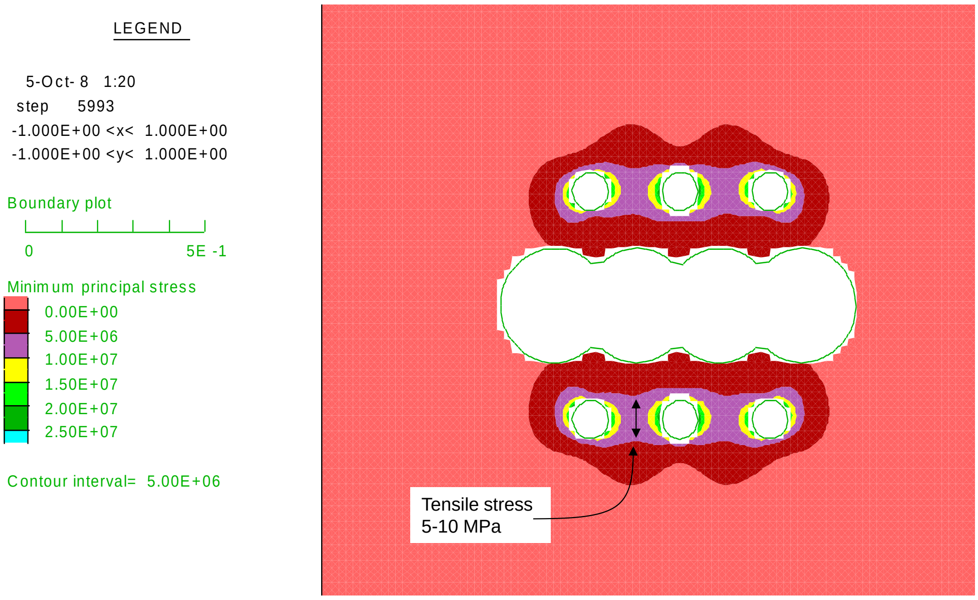


Figure 31: The minor principal stress σ_3 at 20 MPa pressure in the splitting holes

5.7. Conclusions of theoretical studies

In this chapter theoretical aspects are studied to investigate the feasibility for using hydraulic splitting as a method for rock excavation. The following conclusions can be drawn from the theoretical studies:

It is more favorable to perform hydraulic splitting where a free surface is present. The existing stress parallel with the free surface has positive effects for crack initiation and propagation, whereas it might have negative effects for breakdown of the rock beam when the cracks have coalesced. Such situation with a free surface is often encountered in rock engineering, e.g. open pit excavation, slope excavation and enlarging of tunnel sections.

For splitting rock in a tunnel face where the rock is constrained, it is suggested to create first an open cut by e.g. drilling overlapped boreholes. Splitting can then performed towards the open cut. The performed numerical model indicates that this method is feasible for creating the first opening in the tunnel face. Therefore it is believed that hydraulic splitting can be used as an excavation method for a full tunnel face.

The theoretical study shows the splitting devices providing directional splitting pressure is more effective than those providing uniform splitting pressure. Tensile strength and toughness index of the rock have significant influences on crack initiation and propagation. Pre-existing cracks might not have significant influences on the splitting performance. For typical Swedish rock types, a splitting pressure at 15-20 MPa will be sufficient for crack initiation and 50 MPa will be needed for the complete rock breakage.

The current study should, however, be treated as an attempt to investigate the mechanisms of hydraulic splitting in rocks. The major aim is to assess the feasibility of using hydraulic splitting as a rock excavation method. In order to enhance the understanding of the mechanisms, more research work is highly recommended. Based on more studies, it is suggested to have guidelines for determination of, e.g. the required internal pressures and the c-c distance between the splitting holes for different types of rocks and various applications.

6. Field Tests

Within this project, various field tests have been performed by using the equipment as described in Chapter 4. The details of the field tests are given as follows.

6.1. Rock quarries

For rock quarries, it is often necessary to split larger rock blocks into smaller sizes. This is often done manually or by blasting. While it is time-consuming, the manual method is not compatible with Swedish working environment regulations. Blasting interferes other work activities in near areas and protection measures are required. Diamond wire sawing has been used, but it is time-consuming for hard rocks.

The rock quarry industry has been looking for alternative methods. The equipment with directional pressure has been tested in one of the rock quarries in Sweden.

Figure 32: Some examples of split rock blocks

The rock splitter used in the test was 1m meter in length and 60mm in diameter. For rock blocks between 2-3 m^2, one splitter could be sufficient for successful split of the blocks. For larger blocks, 4-5 rock splitters were used with a distance of 40 cm in between. The splitters were pressurized at the same time to create an integrated action on the rock blocks. The tests show that rock splitter with directional pressure could be an efficient alternative tool for rock quarries.

6.2. Högalid Garage, Stockholm (Skanska), June 2009 and February 2010

Högalid Garage is an underground garage located in the central part of Stockholm. The construction work was started at the beginning of 2009. There are apartments, stores and a day care as well as a traffic road nearby the construction site. The use of explosives is therefore restricted. The strict requirements on the blasting works resulted in, however, under-breaks in the rock excavations in the entrance areas. In order to avoid closing the nearby traffic road and disturbances to the neighborhood, non-blasting alternatives were wished to remove the under-breaks.

Different types of rock splitters, with diameter 27mm, 48mm and 64mm, were employed at different occasions. The following observations were made during the different tests.

Test with 27 mm splitter: The bore holes were hand-drilled with a distance about 20-30 cm. Four to five rock splitters of 27mm size were used. The pump pressure was up to 900 bar and cracks could be observed between three holes. However, the rock could not be split and removed, because the openings of the cracks were not large enough.

Test with 48 mm splitter: Six pieces of the rock splitters were prepared and the distance between the drill-holes was 20-30 cm. The holes were drilled by hand-hold machine so that the holes were not as straight as desired. However, the splitters could be installed. The first crack occurred at about 100 bar and the entire block was cracked at around 200 bar. A hydraulic hammer had to be used to remove the cracked rock block (see Figure 33).

Test with 64 mm splitter: The construction of rock splitter was improved based on the experiences from the previous tests. The dimension of the splitter was increased to 64 mm. This type of rock splitter was used for several rock blocks and performed much more efficiently than the smaller ones.

The following lessons are learned from the tests described above:

- Rock splitters of larger diameter have more efficient splitting performance than the smaller ones. Because of the increasing weight, the larger splitters are less easy to handle manually. A machine handling system is desired.
- Cracks could be created by the pressure levels as predicted by the theoretical studies. However, large displacement of boreholes is required for breaking the cracked rock.
- The drilling quality has significant impact on the installation operation. If the drilling quality is poor, it could lead to difficulties for inserting the splitters into the boreholes.


(a)


(b)

Figure 33: (a) Arrangement of the splitters; (b) after removal of the under-break

6.3. City Link Project, Station City, Stockholm (NCC), March 2010

The City Link project is situated in the city centre of Stockholm. The tests were made in an access tunnel across Vattugaraget. Surrounding the access tunnel there is a subway station and a complex for heating-water supply. Therefore restrictions are applied to the tunnel excavations, especially regarding vibration levels and gas emissions. The rock excavation was done by two steps: bottom pilot and roof falling. The tests were performed for the roof falling - to increase the height of the tunnel to the design levels.

Boreholes were drilled in four rows in the tunnel roof, with 10 boreholes in each row. The spacing between the rows is about 30 cm and c/c=40 cm between the holes. Heat-treated steel material is used for the new modified splitters, designed for use in 64 mm borehole.

For each splitting round, 4 splitters were employed. Splitting occurred when the pressured reached 150 – 450 bar and blocks fell down from the roof. A rock volume of about 10 m^3 could be removed successfully for each splitting round.

It was noticed that drilling quality and debris-free in the boreholes were of importance for efficient installation of the equipment.

Figure 34: Splitting the tunnel roof in City Link project in Stockholm

6.4. 2nd Avenue Subway, New York (Skanska), June 2011

A new subway station at the 86th Street and the 2nd Avenue was under construction in the centre of Manhattan, New York. There were rigorous restrictions with respect to the use of explosives for the construction works.

Filed tests with further developed splitters were made at the Croton Water Filtration Plant in Bronx in order to demonstrate that the splitters could be used in Manhattan Schist. Vertical holes with a diameter of 64 mm (2,5”) were drilled by a hand-held drilling machine with a spacing of 300-400 mm. Cracks were observed at a pressure of 200 bar and the final splitting occurred at a pressure of 500 bar, see Figure 35.

It was concluded from the successful tests that the further developed splitter was a competitive option for the rock excavation works. It was highly recommended to employ machine-drilled boreholes for planned splitting works, in order to increase the efficiency of the splitter installation.

Figure 35: Splitting a vertical rock wall with a free surface, Manhattan, New York

6.5. New Karolinska Hospital, Stockholm (Skanska), June 2011

At the site of New Karolinska Hospital, large rock blocks hade to be broken into smaller pieces for transportation. The sizes rock blocks were ranging from one to several cubic meters. Surrounding the site, there is a road with busy traffic and other construction works should not be interrupted. Therefore the splitting method was chosen for breaking the rock blocks.

The work was performed with splitters for 64 mm boreholes. The improved system could sustain 1000 bar without any breakage or leakage. For smaller rock blocks it was often sufficient with one splitter. For large blocks, 3-4 splitters were used simultaneously with spacing of 40-50 cm, see Figure 36.

Most of the rock blocks could be efficiently split at pressure 200-500 bar. For some blocks, additional efforts by hydraulic hammers were necessary. The main reason was that the splitters hade limited expansion ability.

Figure 36: Splitting a large rock block at construction site New Karolinska Hospital

7. Conclusions

Within this project, a preliminary theoretical study as well as field tests have been carried out to investigate the feasibility of using hydraulic splitting as a rock excavation method. The following topics have been included in this project:

- Review of existing non-explosive rock excavation methods;
- Theoretical rock mechanics studies to obtain enhanced knowledge on crack propagations between the boreholes and rock breaking mechanisms. Studies have also done to investigate the possibility of excavating a full tunnel face with the hydraulic splitting technology;
- Field tests to uncover technical issues regarding equipment and construction performance.

The theoretical studies and field tests conducted within this project show that hydraulic splitting is a feasible rock excavation method with promising technical potentials.

The theoretical studies indicates that a device with a capacity of providing directional splitting pressure p_s^c > 15 MPa (150 bar) will cover the most of rock conditions for crack initiation. For crack propagations, additional pressure is required. The numerical simulations performed in this study for typical Swedish hard rock types indicate that when the internal pressure increases to 14 MPa, intensive shear failure appears over almost entire area which is intended to be excavated. The model could not reach numerical equilibrium at this stage, which can be interpreted that an overall break-down of the rock beam has been achieved by the splitting pressure.

Tensile strength and toughness index of the rock have significant influences on crack initiation and propagation, whereas pre-existing cracks might not have significant influences on the splitting performance.

The theoretical studies also display that it is more favorable to perform hydraulic splitting where a free surface is present. The existing stress parallel with the free surface has advantageous effects for crack initiation and propagation, whereas it might have negative effects for breakdown of the rock beam when the cracks have coalesced. Such situation with a free surface is often encountered in rock engineering, e.g. open pit excavation, slope excavation and enlarging of tunnel sections.

For a tunnel face, where the rock is constrained, it is suggested to create first an open-cut by e.g. drilling overlapped boreholes. Splitting can then performed towards the open-cut. The performed numerical model indicates that this method is feasible for creating the first open-cut in the tunnel face. Therefore it is believed that hydraulic splitting has potential to be used as an excavation method for a full tunnel face.

Though difficulties have been encountered in the field tests, all of the tests were performed with successful results. Most of the difficulties were caused by the boreholes drilled by hand-hold equipment. These holes had less precision regarding the borehole dimensions and surface quality. The equipment used in the tests had also some limitations which need to be improved. One of the major issues has been the post-expansion capacity after cracks have been created in the rock.

The spacing between boreholes was in the range between 40 and 50 cm in the field tests. This spacing was first estimated by theoretical analyses and then was proven feasible. In the most of the cases, where the rock types were hard rock, the splitting pressure ranged from 15 to 20 MPa (150 – 200 bar). In the some cases, 20 – 50 MPa splitting pressure was required. The tests show clearly that operations with several splitters interacting with each other had significant efficiency advantages. It is believed that high efficiency could be achieved with an automated system, where mechanical arms handle the hydraulic splitters while the pumps, hoses and other equipment are mounted on a vehicle.

Regarding working safety issues, the following remarks could be made from the results of this project:

Hydraulic splitting is considered as a safe method for rock excavations, which does not associate with any dangerous explosions, harmful gas emissions and vibrations. This means that hydraulic splitting could create a more safety friendly working environment compared with blasting. The splitting technology enables that all other works including drillings, rock supports or installations etc. could be carried out in parallel with excavations works. Zero emission of toxic gases allows construction works be performed without interruptions. These advantages could shorten the time for excavation working circles, contributing overall construction efficiency.

The working pressure of the splitters is about 700-1000 bar. This high pressure could lead to personal injuries caused by sudden moving pipes associated with a sudden breakage. Therefore precaution measures must be taken with regards to the hydraulic systems with high pressure.

With consideration of environmental issues, water is strongly recommended being used as the hydraulic media. A large amount of leakage of hydraulic oil at a construction site would otherwise violate the environmental regulations and decontamination measures would be mandatory.

8. Recommendations for further development

The studies performed in this project have obtained encouraging results regarding using hydraulic splitting as a rock excavation method. Recommendations of future studies are made in the following topics.

- Excavation of a full tunnel face: A preliminary numerical simulation was made in this project indicating that it would be feasible to excavate a full tunnel face. It would be desirable to perform field tests to verify the feasibility. More key technical issues for further development could be identified from these field tests. For planning and directing the field tests, more detailed theoretical studies, e.g. numerical simulations are highly recommended.
- Equipment development: The current splitter developed and tested within this project has shown promising results. A key limitation of the equipment has however discovered from the field tests, namely the limited expansion capacity. New solutions for increasing the expansion capacity are thus necessary. These new solutions have to be tested in the field.
- Automation of the entire splitting process: Working efficiency in industry scale is a key issue for implementation of the technology in rock engineering. It is recommended to perform a comprehensive study on the entire automatized process from drilling of boreholes and handling of splitters, to control of hydraulic system and remove of the split rocks.

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