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Methodology study for documentation and 3D modelling of blast induced fractures

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SKB

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Preface

SKB is moving closer to submitting the license application for final disposal of spent nuclear fuel. The licence application will be supported by a safety assessment (SR-Site). In spite of many experiments and international workshops as regards the EDZ there is still a dearth of relevant data and information. The SR-Site project has identified the need for qualified descriptions and data, especially on the axial hydraulic properties used to calculate the transport resistance for radionuclide transport in the event of the canister and buffer being impaired, or the transport capacity of components up to the disposal holes which may affect the repository performance of the bentonite buffer or corrode copper.

SKB has initiated an EDZ programme (named Zuse) 2007–2009 to:

- establish the current knowledge base on EDZ with particular focus on the axial hydraulic properties along the underground openings,

- devise methods to infer or measure the EDZ at different times during the repository construction and operation before closure and to find a basis for acceptance criteria,

- propose demonstration tests where the methods are used in situ to qualify appropriate data for use in safety cases.

This report contributes to the Zuse project by proposing a methodology to investigate and model the geometries of the blasting induced fractures.

Stockholm 2008-07-01

Rolf Christiansson

Summary

The purpose of this activity as part of the Zuse project was to test whether it is possible to produce a 3D model of blast induced fractures around a tunnel and also to find a methodology suitable for large scale studies. The purpose of the studies is to increase the understanding of the excavation damage zone (EDZ) and the possibility of an existing continuous EDZ along the tunnel.

For the investigation, an old test area in the Q tunnel at the Äspö Hard Rock Laboratory was selected, where slabs were excavated in 2003 to investigate the fracture pattern around the contour holes of a blasted tunnel /Olsson et al. 2004/.

The rock walls of the excavated niche were studied and documented in the tunnel, while the excavated rock slabs were documented above ground.

The work flow included photo documentation of both sides. The photos taken in the tunnel had to be rectified and then the fractures were vectorized automatically in a vectorization program, generating AutoCad® DWG-files as output. The vectorized fractures were then moved to MicroStation®/RVS where they were interpreted and connected into continuous line strings. The digitized slab and rock sides were then moved to the correct position in 3D space. Finally, a 3D model was made in RVS where the fracture traces were connected into undulating fracture planes in 3D.

The conclusion is that it is possible to build a 3D model; the model is presented in Chapter 3.5. However, the age and condition of the slabs may have influenced the quality of the model in this study.

The quality of a model that can be built in a future investigation, should be much better if the surveys are adapted to the investigation at hand and the slabs and rock sides are fresh and in better condition.

The validity of a model depends on the density of the investigation data. There is also always a risk of over interpretation; the wish to identify a fracture from one section to the next can lead to an interpretation of the fractures as more persistent than they actually are. The fracture patterns in the sections are expected to be similar, but this does not imply that it is the same fractures that are seen. There is also a risk when terminating a facture since it can interact with other fractures in ways that cannot be seen in the model, partly because small fractures cannot be modelled for practical reasons.

Consequently, a model can give a very good view of the fracture pattern in the tunnel wall and hence an increased understanding and knowledge. It is, however, always important to remember that it represents a model of the reality and not the reality itself.

A recommended methodology for future investigations is presented in Chapter 5. In Chapter 6 a study of a possible future development, with in situ documentation of the fractures in the rock without excavating slabs, is discussed.

Sammanfattning

Detta projekt har till syfte att testa huruvida det är möjligt att åstadkomma en 3D-modell av sprängskadeinducerade sprickor runt en tunnel och att hitta en metodik för att göra denna typ av studie i ett större försök. Syftet med en sådan större studie är att öka förståelsen för hur sprängskadezonen ser ut och framförallt att kunna bedöma om det finns en möjlighet till en kontinuerlig skadezon längs tunneln.

Som testområde valdes ett försöksområde i Q-tunneln vid Äspölaboratoriet, där man under 2003 sågade ut skivor i bergväggen för att studera sprickutbredningen runt konturhålen i en sprängd tunnel /Olsson et al. 2004/.

De kvarstående sidorna i den utsågade nischen studerades och dokumenterades i tunneln, medan de utsågade skivorna dokumenterades ovan jord.

Arbetsgången var att båda sidor fotodokumenterades, de foton som togs av bergssidorna i tunneln fick rektifieras. Sedan vektoriserades sprickorna automatiskt i ett vektoriseringspro-gram som lämnade AutoCad® DWG-filer som resultat. De vektoriserade sprickorna togs in i MicroStation®/RVS där de tolkades och knöts till sammanhållna linjesträngar. De digitaliserade skiv- och bergssidorna lades sedan in på rätt plats i 3D-rymden. Slutligen gjordes en 3D-modellering i RVS där sprickspåren knöts samman till vindlande sprickplan i 3D.

Slutsatsen blir att det är fullt möjligt att bygga en modell i 3D, modellen presenteras i kapitel 3.5. Kvaliteten på modellen har dock påverkats av att skivorna inte mätts in före uttag och passningen i 3D därför blev lite ungefärlig, och att skivornas ålder och skick gjorde dem svårtolkade.

Beträffande den modell som kan byggas i 3D vid ett kommande försök så kan kvaliteten bli mycket bättre om inmätningarna är anpassade till studien och skivor och bergssidor är färska och därmed i bättre skick.

Validiteten för modellen blir beroende på tätheten i undersökningen. Det finns också alltid en risk att övertolka, viljan att hitta en spricka från sektion till sektion kan leda till att sprickorna kan tolkas att vara mer uthålliga än de är. Sprickmönstret i de studerade sektionerna kommer att vara likartat men det betyder inte att det är samma sprickor man ser. På samma sätt finns det risker med att avsluta en spricka, den kan samverka med andra sprickor på ett sätt som inte framkommer i modellen, bland annat därför att mycket små sprickor inte kan modelleras av praktiska skäl.

En modell kan alltså ge en mycket god bild av sprickmönstret i tunnelväggen och därigenom ge en ökad förståelse och kunskap. Men man måste alltid komma ihåg att det är en modell av verkligheten man betraktar och inte verkligheten.

En rekommenderad metodik för kommande undersökningar presenteras i kapitel 5. I kapitel 6 diskuteras en studie av en tänkbar framtida utveckling som innebär dokumentation av sprick-orna på plats i berget utan uttag av skivor.

Contents

1 Introduction

1.1 Background

An additional tunnel excavation was made at the Äspö Hard Rock Laboratory (Äspö HRL) during 2003. The tunnel is located at the –450 metres above sea level, level close to the shaft. The tunnel was specially designed for a rock mechanics experiment, the Äspö Pillar Stability Experiment (APSE) /Andersson 2007/.

In different locations along the tunnel the excavation damage zone (EDZ) from blasting was examined by cutting slots in the wall and roof. Five vertical slots were made in the walls together with one horizontal slot. A slot was also made in the floor. The slots were made by sawing a number of parallel cuts into the rock. Normally two horizontal cuts and 4 to 5 vertical cuts were sawed. The distances between the cuts were adjusted to the force required to loosen the slabs between the cuts. After the slabs are removed a penetrative dye was sprayed on the cleaned slot surfaces causing the fractures to appear very clearly. The result from this examination was published in a SKB-report /Olsson et al. 2004/.

For the identification and measuring of blast induced fractures there has to be at least one visible half-pipe. A typical fracture pattern is shown in Figure 1-1 where there are some fractures originating from the half-pipe (blasting fractures) and other fractures, induced or natural, inside the rock mass. The lengths of the blasting fractures are influenced by the explosive itself, the coupling ratio (diameter of charge/diameter of hole), the delay time, spacing, natural fractures, the rock and presence or absence of water. Induced fractures are fractures starting near the tunnel contour but not originating from the hole itself. These fractures are probably caused by the high stresses and released by the blasting process or by the redistribution of stresses due to excavation of the tunnel. The natural fractures are determined by geological conditions. They could be opened or filled by some minerals. During the blasting process these fractures might expand. The natural fractures often seem to have the same direction in the walls.
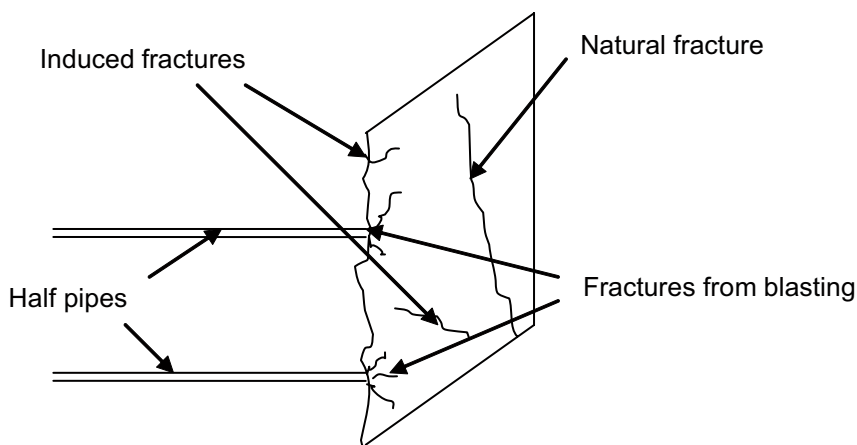

Figure 1-1. *Typical fracture pattern /Olsson et al. 2004/.*

1.2 Scope of work

The purpose of this study was to investigate the possibility of creating a 3D model of the blast induced fractures adjacent to the tunnel contour holes.

A very important issue for SKB is whether blasting could result in persistent fractures parallel to the tunnel. In the earlier TASQ-study /Olsson et al. 2004/ there was no evidence of a persistent and continuous EDZ, the fractures here were only classified as local fractures. However, there might be a risk that fractures from one round could continue to the next round due to intensification from the bottom charges. Probably there is a higher risk of continuous natural fractures. In order to dig deeper into this an idea came up to investigate the possibility of creating a 3D model of fractures in a tunnel wall. It was decided to use the information from the slots and slabs left from the study of the EDZ in the TASQ-tunnel.

1.3 General conditions

Since this is a methodology study, using old material, it is important to emphasize that the conditions for the work are somewhat restricted. The surveying was not adapted to the investigation at hand. Old slots and slabs were used, which meant that they were not in the best condition. The slot walls were wet and dirty and fractures were filled with old residues. The slabs were worn and dirty with pieces missing. The material was sufficient for a methodology study but the value of the created model itself is limited.

A new study, planned and adapted for 3D modelling from the beginning, would clearly benefit from having new and more applicable input data for building a valid model.
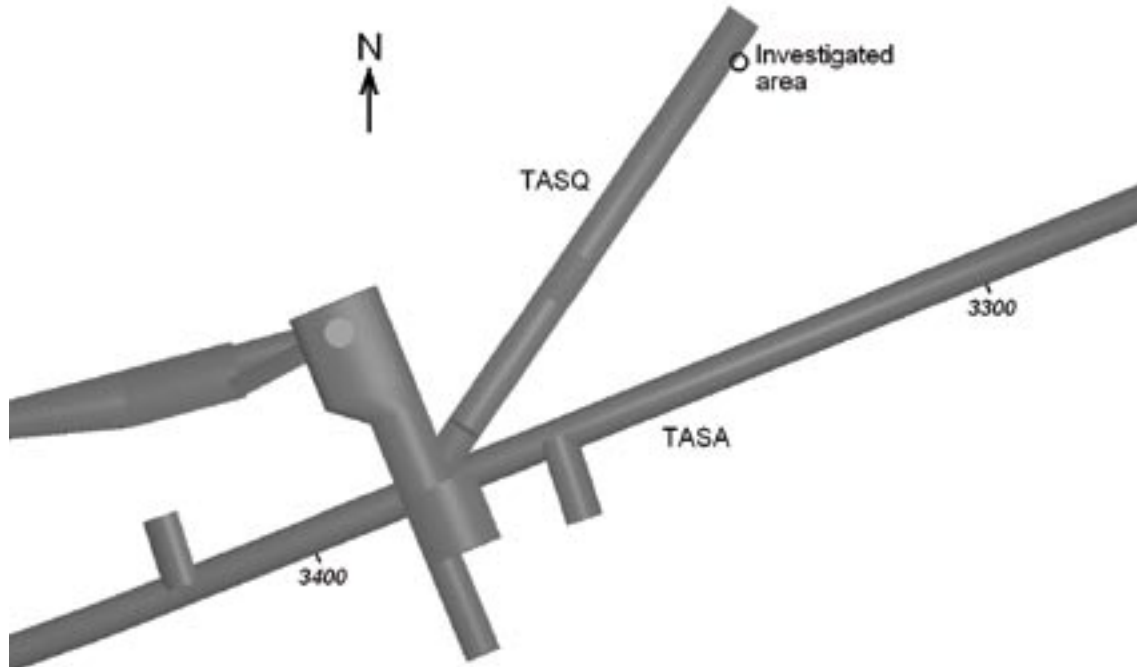

Figure 1-2. *The investigated tunnel area in the Q tunnel at Äspö HRL.*

2 Work flow

2.1 Field investigations

2.1.1 EDZ in slots

In this investigation the task was to examine the EDZ once again in order to see if fractures could be digitized and modelled in 3D. For this the former test sections 2 and 3 /Olsson et al. 2004/ and the horizontal slot between these sections were chosen. All the test sections are situated on the right wall of the tunnel. Test section 2 covers the first part of round 33 in the tunnel and test section 3 covers an area roughly 2 m further on in the round. Between these two areas there also is a horizontal slot, see Figure 2-1, Figure 2-2 and Figure 2-3.
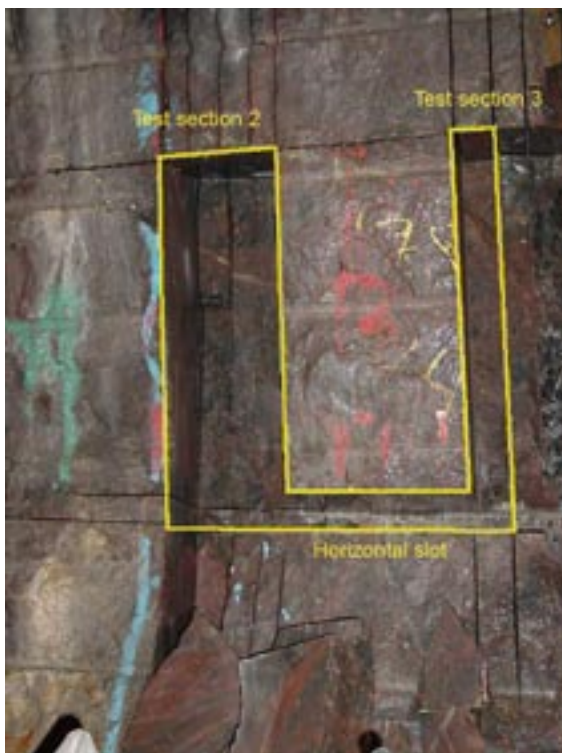

Figure 2-1. *Test area with some of the slabs.*
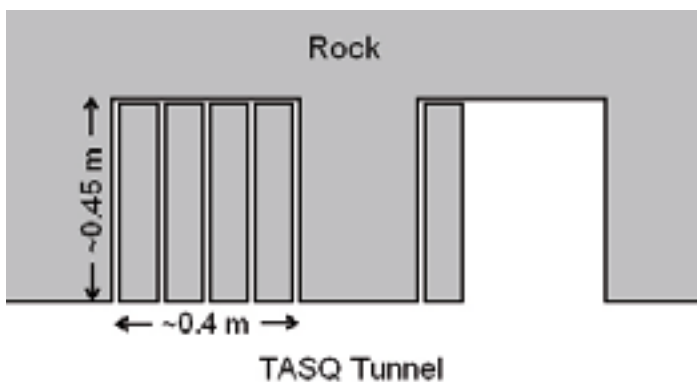
Figure 2-2. *Schematic horizontal section through the investigated area.*
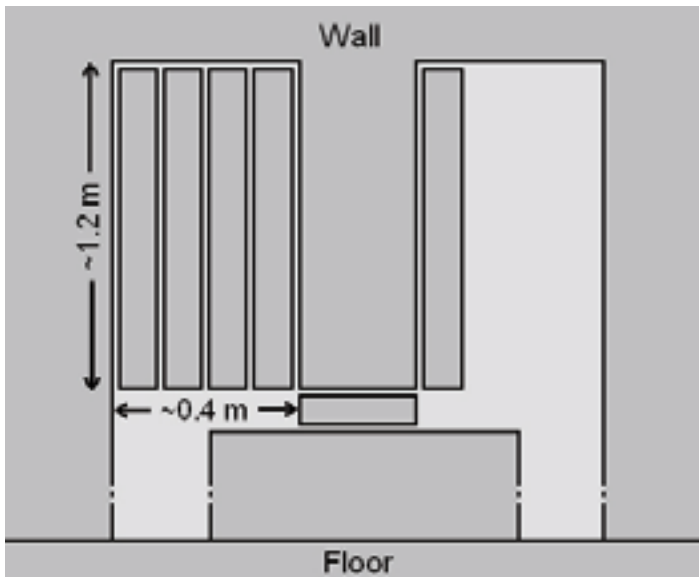
Figure 2-3. *Schematic vertical view of the investigated area.*

In preparation, a scaffold was constructed in front of the slots and the slots were cleaned by high pressure water. However, it was not possible to clean the fractures completely from the color of the old penetrant. After cleaning, the surfaces of the slots were dried by fans and a heat gun. Markers were placed on the surfaces and the distances between these markers were measured. The markers were later used for rectification. Photos were taken and then penetrants were sprayed on the vertical surfaces to identify the fractures. In some of the surfaces we had problems with water leakage from the tunnel roof. As soon as the penetrants had dried, photos were taken on the surfaces. Unfortunately it was not possible to use penetrants on the surfaces of the horizontal slot as these surfaces could not be properly cleaned.

Figure 2-4. *The different steps from washed surface to photographing.*

The light was just sufficient if used with tripod and proper technique. Camera flashes were used for the free hand photos, but not when photographing the rock surfaces due to difference in white balance between the existing light and the flash and also to avoid reflections on the rock surface from the flash. The camera used for the rock surface images was a Nikon D200, mounted on a tripod, with a Nikon 35 mm f2.0 lens, selected for its sharpness and lack of distortion compared to a zoom lens used in the same range. A Tokina 12–24 mm f4.0 lens was also used to get wide angle shots of the rock when the distance between the camera and the tunnel wall was too short for the Nikon 35 mm. A remote release cable had to be used due to the poor light and that the platform was not stable enough to ensure that that there was no camera movement when taking the image. The photos were taken in bursts of 5–15 images while nobody was moving on the platform, to ensure that there was at least one usable image of a particular surface.

The work done on the rock and with the camera was also documented by using a standard pocket camera equipped with an external flash. The images of the work have been useful as a reference to remember what was done and also when describing to others what was done.

2.1.2 EDZ in slabs

The slabs from the earlier sawing have been stored in a tent at Äspö since the last investigation. The slabs from our test area (test sections 2 and 3) were transported to the car washing hall at Äspö. Here the slabs were washed and labelled. Small holes were drilled around the edges of the slabs and expansion-shell bolts were attached, to be used as reference points during the 3D fitting of the opposing sides of the slabs. Some of the slabs were damaged and it was a puzzle job to put all pieces together, see Figure 2-6.

After washing, the slabs were dried and then the penetrants were sprayed on, after which a developer was sprayed on the dried surface. The developer gave a much better contrast in the pictures and the fractures were therefore easier to digitize. However there is a risk that information can be lost since finer fractures will be obscured. The slabs were then rolled in under a camera to a fixed position.
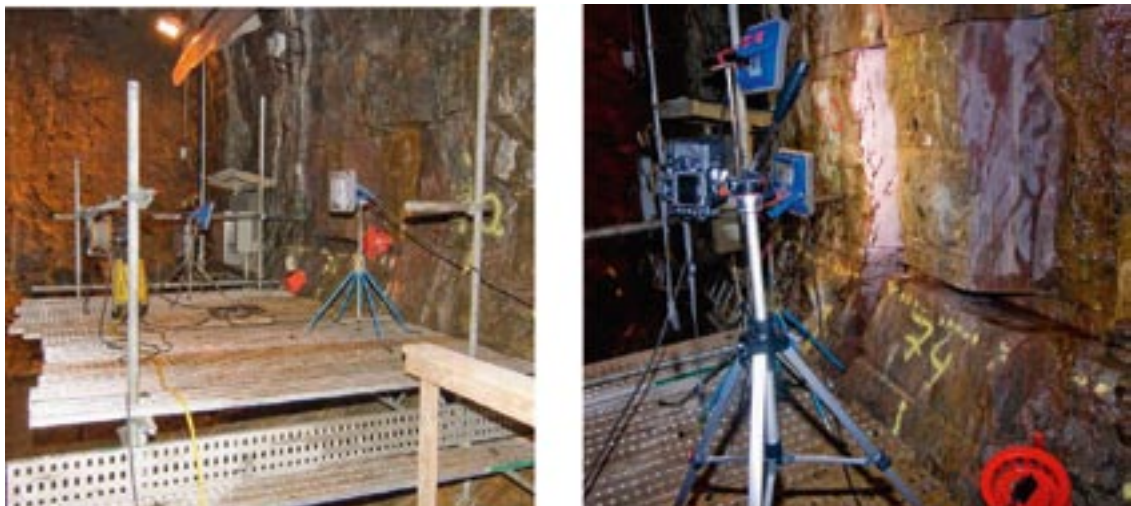
Figure 2-5. *Photo arrangement in the tunnel.*

Figure 2-6. *Pieces of the slabs.*

The camera was mounted at a height that gave a field of view that accommodated the largest slab. The camera was then aimed with a laser sight and a plumb line to make sure that the camera was pointing absolutely vertically in order to minimize the distortion of the images. This installation also has the benefit that all the images of the slabs have the same scale and that rectification can be avoided, see Figure 2-7.

Lights where placed on the floor beneath the camera and aimed to the point where the slabs where placed for photographing.

Figure 2-7. *The photo arrangement of the slabs.*

Pictures of a slab with its fractures were taken both with and without a reference scale. The scale is very useful when determining distances in the image and for cross-checking of scales but pictures are also taken without the scale since it can obscure. The slab was then turned over on the other side and the procedure was repeated. The handling of the slabs was rather heavy and the whole procedure was rather time consuming but it was possible to process one slab per hour.
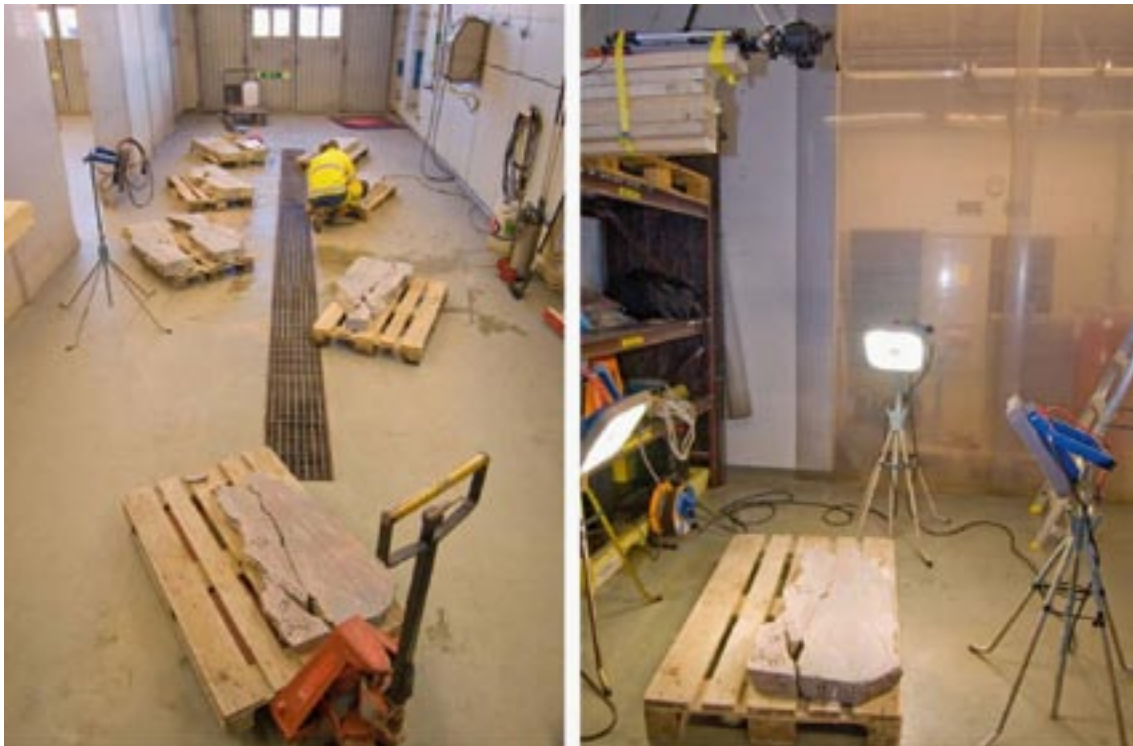
To eliminate the need for rectification the camera was equipped with a lens with very little optical distortion.

The camera was remote controlled during the photo session making it possible to make changes to the settings in the camera and to compensate for differences in the slabs. One other benefit of having the camera connected to a computer is that the images are downloaded and shown on screen directly when taken. This means that they can be evaluated for exposure and focus directly and if they failed another image can immediately be taken.

2.2   Rectification

Six points on each section side were marked in ink before photographing and the distances between them were measured and recorded. In a 2D CAD file the pattern of the markers were recreated as a basis for the rectification of the photos, see Figure 2-8.

With the CAD drawing as a base, the markings on the rock in the image were placed on top of the vertices in the CAD drawing. This was done in the program Global Mapper© by Global Mapper Software, LLC. The program then moves and stretches the pixels of the rock image ending up with an image that has the dimensions and appearance of a picture taken perpendicular to the rock surface.

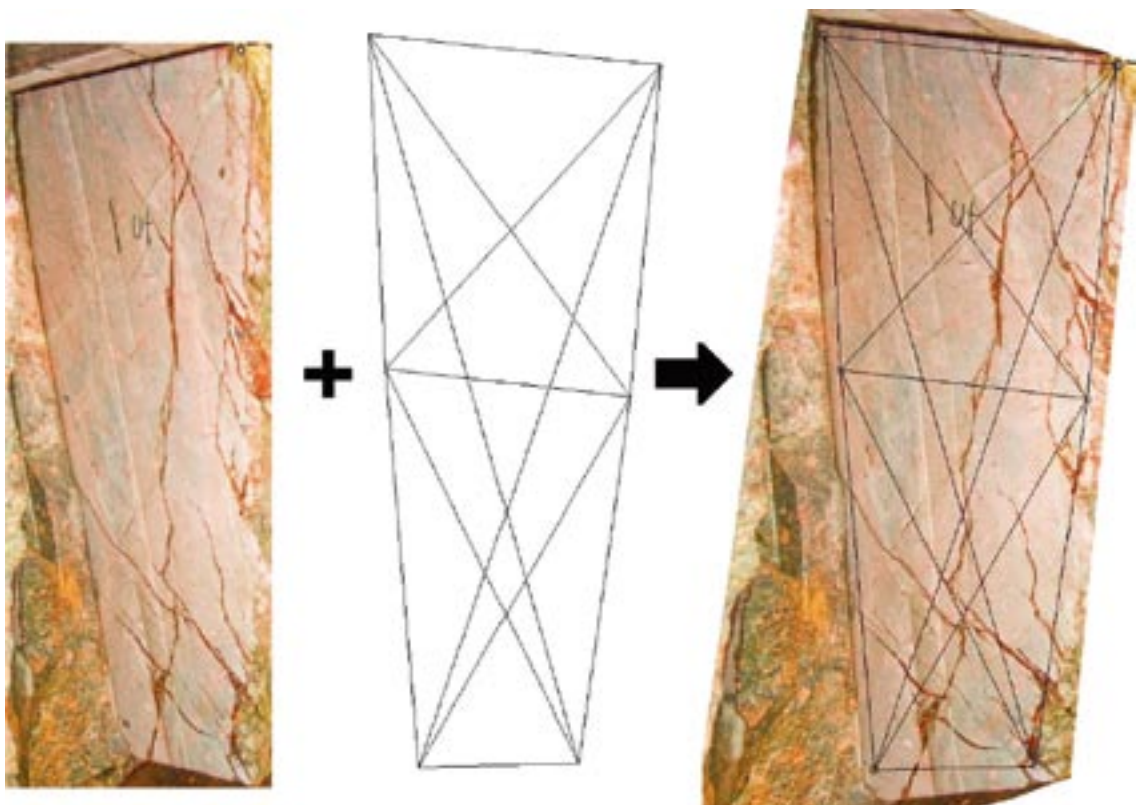There was no need to rectify the photos of the rock slabs, see section 2.1.2.

Figure 2-8. *Example of section photo, before and after rectification.*

2.3   Vectorization

Vectorization of the investigated sections was performed as follows:

- the image was opened in Adobe Photoshop© and the interesting part was cut out,

- the contrast was increased, the black and white cut off was adjusted and a noise reduction filter was run on the image to reduce the effect of the rock structure,

- an equalization algorithm was run on the image to even out the light difference in the image. This left the dark fractures very visible against the near white rock background,

- the contrast was adjusted to maximize the dynamic range and the red, green and blue channel were weighted and mixed into a gray scale image,

- a cut off for the level of gray that separates feature from background was set, and the image converted to black and white where black is a feature and white is the background,

- an automated vectorization program interpreting the B&W image into vectors was run,

- the bore pipes and fix points were added to the vector layers and the features that were considered as noise were filtered out before exporting to DWG for further work.

After vectorization, a calculation of the fracture area in percent of the total area related to the distance from the tunnel wall was made. Figure 2-10.
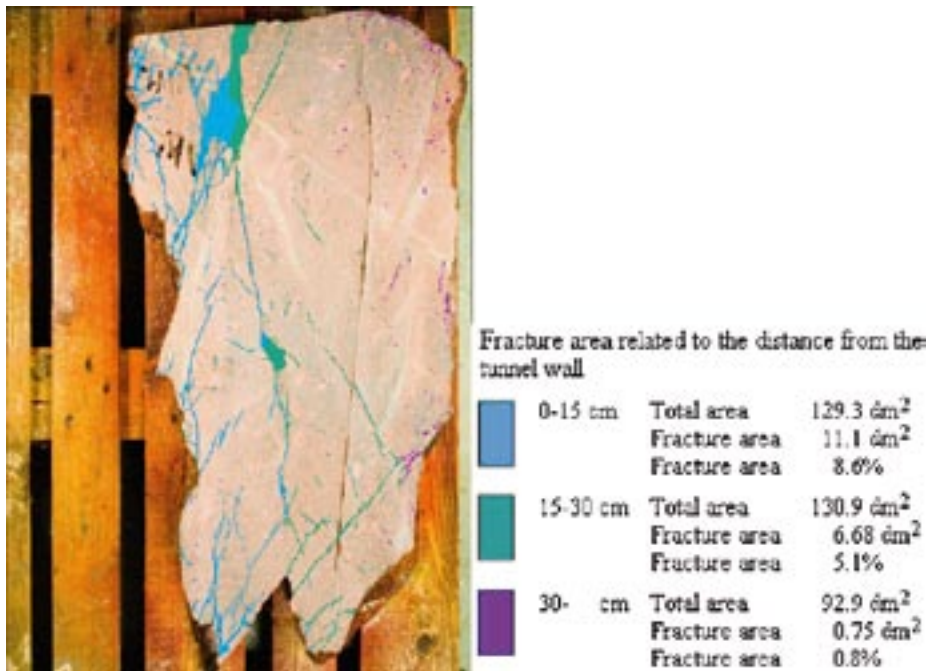

Figure 2-9. *Vectorized section from a rock slab.*

Fracture area related to the distance from the tunnel wall

0–15 cm	Total area	129.3 dm²	
	Fracture area	11.1 dm²	
	Fracture area	8.6%	
15–30 cm	Total area	130.9 dm²	
	Fracture area	6.68 dm²	
	Fracture area	5.1%	
30– cm	Total area	92.9 dm²	
	Fracture area	0.75 dm²	
	Fracture area	0.8%	

Figure 2-10. *The evaluated fracture area related to the distance from the tunnel.*

2.4 3D transformation

2.4.1 Steps

The 3D transformation included the following steps:

- setting up a model in 3D space,
- creation of 2D planes in 3D space representing the position sides of the cutting slots,
- scaling of each scanned section. This step can be avoided if the proper scale is used when scanning,
- attaching files as reference to the model,
- orienting the scanned section to the correct 2D plane in 3D space,
- moving and rotating the scanned section in this plane to place it correctly in 3D space.

2.4.2 Model setup

The modelling work was performed in SKB's Rock Visualization System (RVS), an application based on Bentley MicroStation© /Curtis et al. 2007/, and also directly in Bentley MicroStation© 3D CAD.

A model was created covering the volume of interest. The model volume represented 1.3 m along the tunnel, with a depth of 0.6 m and height of 1.4 m. The model was created and saved in the Äspö96 system.

The fracture planes were created using the RVS modelling function *Surface by Profiles* which connects selected line strings to a surface, spanning the area between the line strings without extrapolation.

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2.4.3   Creation of 2D planes

The first step was to create 2D planes in 3D space representing the position sides of the cutting slots. This was based on the laser scanning by BBK AB of the Q tunnel performed after extraction of the rock slabs. This laser scanning was, however, made for other purposes and hence, was not adapted for this application.

The laser data was triangulated using RVS surface modelling functions. These are not ideal for these kinds of data since they are triangulating using a 2D projection of the 3D data. The surface becomes very rough and with triangles as long needles near the edges of the cutting slots, see Figure 2-11.

The position of the two outer slot walls in test section 2 and the only investigated slot wall in test section 3 investigated down in the tunnel, could be roughly recreated using the RVS triangulated mesh, representing the measured tunnel walls, see Figure 2-11. The accuracy of the position of the surfaces representing the outer slot walls is estimated to be c. ± 1 cm.

The intermediate surfaces in test section 2, representing the sides of the rock slabs, were created by dividing the area between the outer walls to the four slabs, using an approximate thickness for each slab measured in lab. The difference in angle between the outer surfaces was also evenly distributed between the slabs, thus making a gradual shift from the orientation of one outer wall to the other. Since the cutting slots are not parallel, this is a rather crude approximation with an estimated accuracy of c. ± 2 cm. However, this is considered to be acceptable for the current methodology study.

The other surface in test section 3, representing the outer wall of the first rock slab, was roughly created using the RVS triangulated mesh, representing the measured tunnel walls.

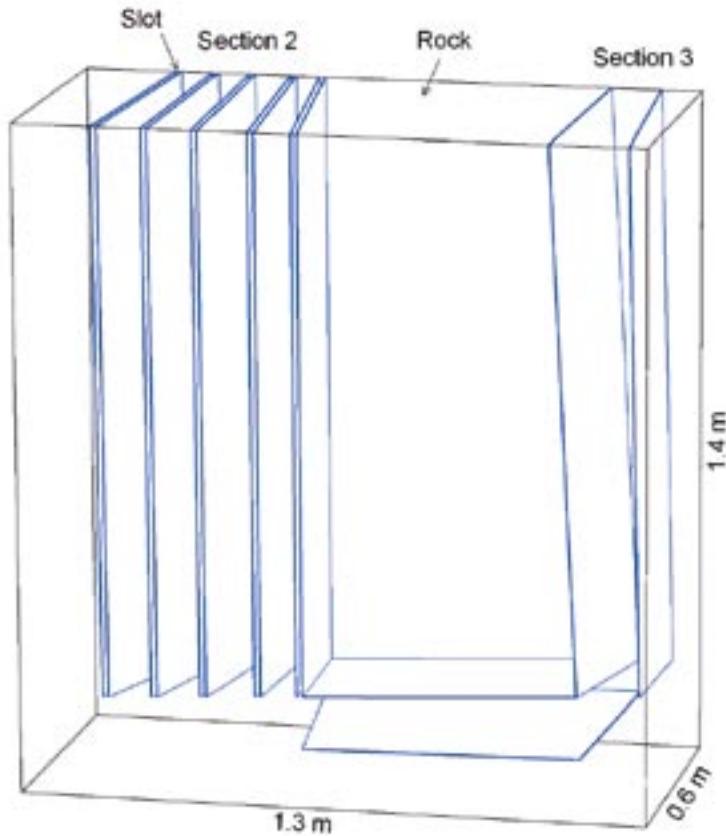***Figure 2-11.*** *The investigated area, photo and mesh created from laser data.*

Figure 2-12. *2D planes in 3D space representing the position sides of the cutting slots.*

2.4.4 Scaling of each scanned section

Before the vectorized planes of test section 2 could be adjusted and included in the model, they had to be corrected for scale. This step would have been unnecessary if the correct scale had been used when rectifying and vectorizing. This lesson was learned during the project and the vectorized planes of test section 3 and the horizontal slot was created using the correct scale and no scaling was necessary.

2.4.5 Fitting of scanned sections in 3D space

The vectorized sections were then placed on the 3D planes, representing the slot walls, and each section had to be scaled, rotated and moved on the plane to fit correctly in 3D space. Also here, the laser modelled surface was used as a basis but also the marked position of the bore-pipes. The fitting was visual and the accuracy again estimated to be c. ± 1 cm.

The horizontal slot walls were in bad condition, were hard to vectorize and hard to fit in 3D space. The accuracy here was estimated to be c. ± 2 cm.
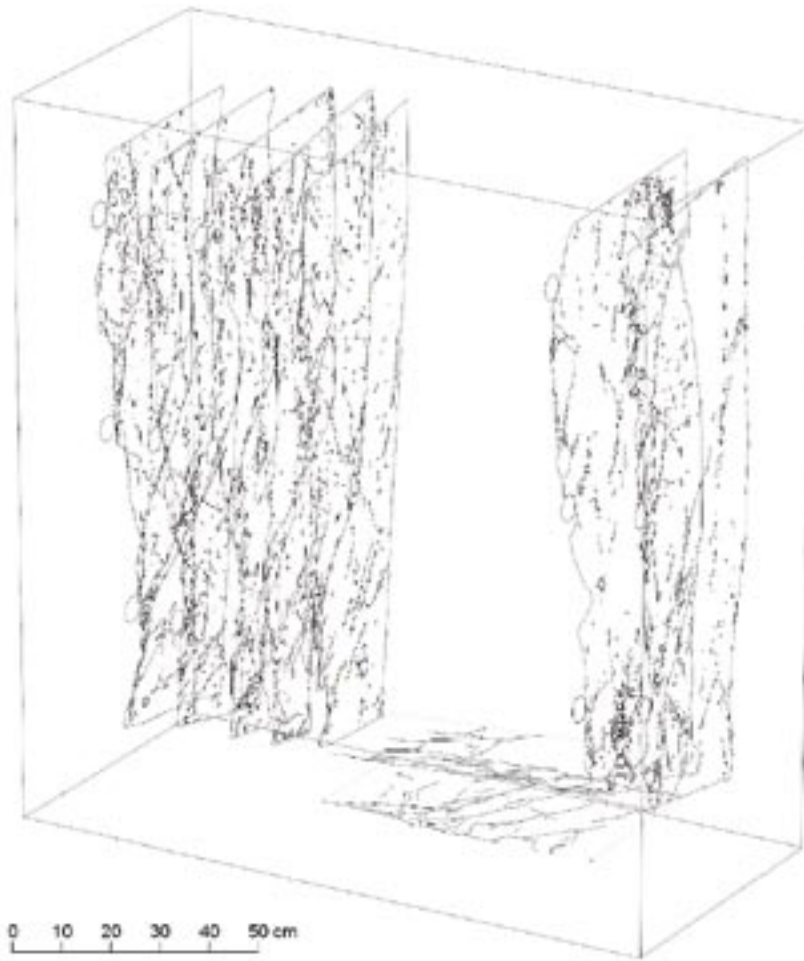
Figure 2-13. *The scanned and vectorized sections moved into 3D space. The bore-pipes on the tunnel wall are visible as small circles.*

2.5 3D modeling

2.5.1 Data selection

When modelling in 3D, the vectorized and selected fracture traces are connected to form undulating, modelled fracture planes, see Figure 2-17. Before this can be done, however, the small line segments (se Chapter 2.3 above) must be connected into longer linestrings or polylines. This is a suitable opportunity to make a selection and classification of the different fracture traces to use as a basis for the 3D interpretation.

As the precision in the 3D fitting was quite rough, only one profile per cutting slot was used rather than both profiles on each side of the cutting slot. This decision was taken since an error in position in the cm scale between two profiles less than one cm apart generated strange geometrical effects on the modelled fractures. It was also judged that two sections so close to each other would give very little in terms of additional information.

Hence, sections placed approximately 10 cm apart, the approximate thickness of the rock slabs, were used for the modelling and possible errors in the fitting had lesser relative impact on the geometry of the modelled fractures. When modelling, the opposite sections of the same cutting slot, that were not used, were also viewed and interpreted as supporting information to the sections used.

20
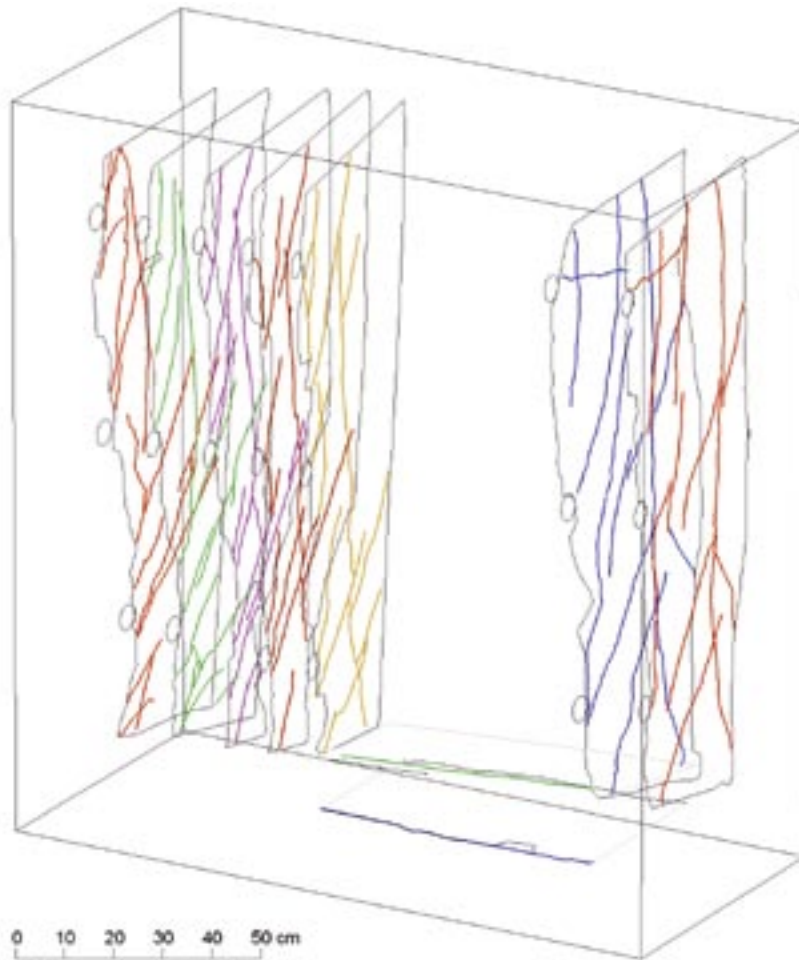
Figure 2-14. *All selected fracture traces in 3D space.*

The vectorization process results in too much information for it to be directly used to build a model. There needs to be focus on a fewer number of some of the more interesting fractures in order to connect them into planes. In this study we focused on some of the most obvious blasting fractures originating from the half pipes, some clearly induced fractures and finally a couple of very obvious natural fractures that could be seen in at least two cuts.

Figure 2-15. *The fracture pattern is clearly denser close to the bore pipes.*

When the fracture traces are selected and connected, fracture swarms can be represented by a single, continuous fracture trace. This is done when the small fractures are connected and together acting as one continuous fracture; see also Chapters 3.5.1 and 5.5 below.

2.5.2 Fracture Modelling

The selected fracture traces were viewed in 3D and a visual evaluation was made of which traces between the different sections could be connecte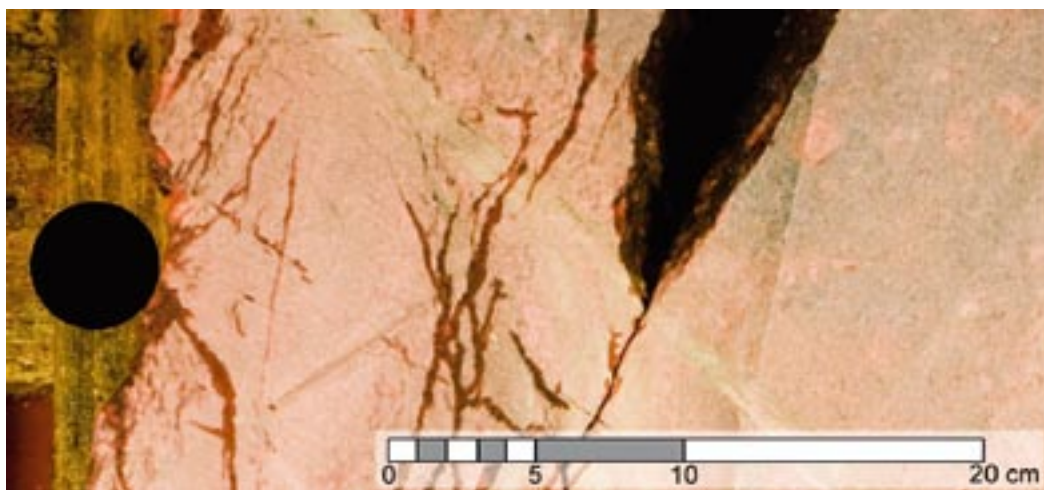d into a modelled structure. In this process, three main factors for building the 3D network were used to support the interpretation of the different structures.

The first is simple geometrical considerations; the fracture traces to be connected have to fit geometrically to form logical and plausible fracture geometry. The studied sections gave a good view of how the different fractures were connected and cut off by each other. When the different sections were viewed in parallel, the fracture pattern could, to some extent, be recognized and individual fractures identified between the sections.

The second criterion for connecting fracture traces was the classification of the different traces from the investigations. Here, knowledge of the typical characteristics of both natural and blast induced fractures was used.

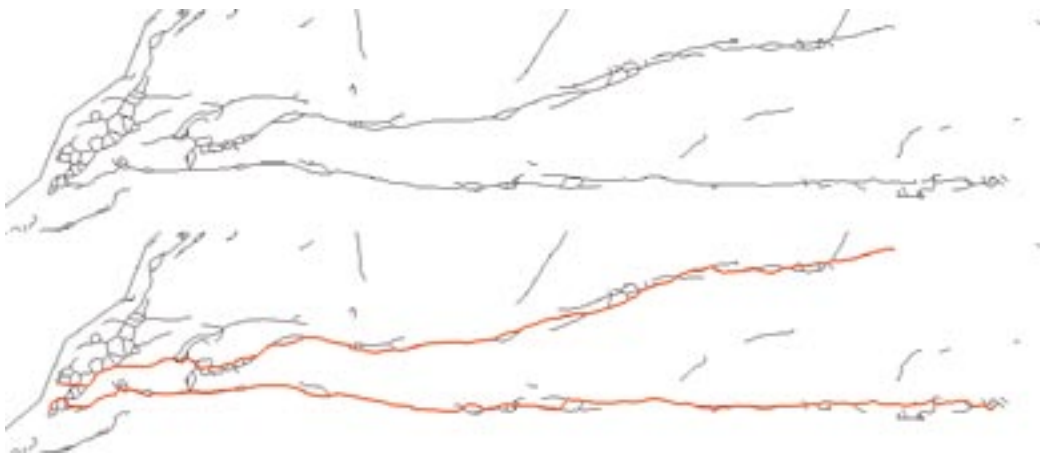
Figure 2-16. *"Swarms" of smaller fractures shown above, simplified into two continuous fracture traces, shown below in red.*
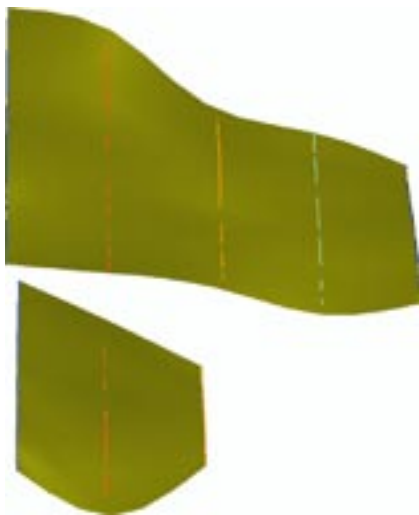

Figure 2-17. *Example of two modelled fractures where one stretches over five sections and the other over three.*

The third criterion was an evaluation of the overall fracture pattern formed by the modelled fractures. As the model was growing, the fracture network formed was continuously reviewed and evaluated.

When connecting fracture traces into a fracture surface the some fractures can be identified in all five sections investigated while others only are found in some of the sections. This indicates that all the fractures are not continuous through the entire length of the tunnel. However, such conclusions are only very tentative since this is a methodology study where focus is not on the quality or validity of the model.

2.5.3 The modelled fractures

General

While we already have pointed out that this is a methodology study where the ability to create a model, rather than the actual model itself, has been in focus, we are still presenting the created model below. Some interesting observations and experiences from the model can be made, which are important for future modelling work.

A total number of 31 fractures have been modelled. Of those, 19 fractures are in test section 2, where we have investigated 4 rock slabs; 11 are in test section 3, where we have investigated 1 rock slab and 1 is in the horizontal opening between test sections 2 and 3, where 1 rock slab has been extracted.

0 10 20 30 40 50 cm
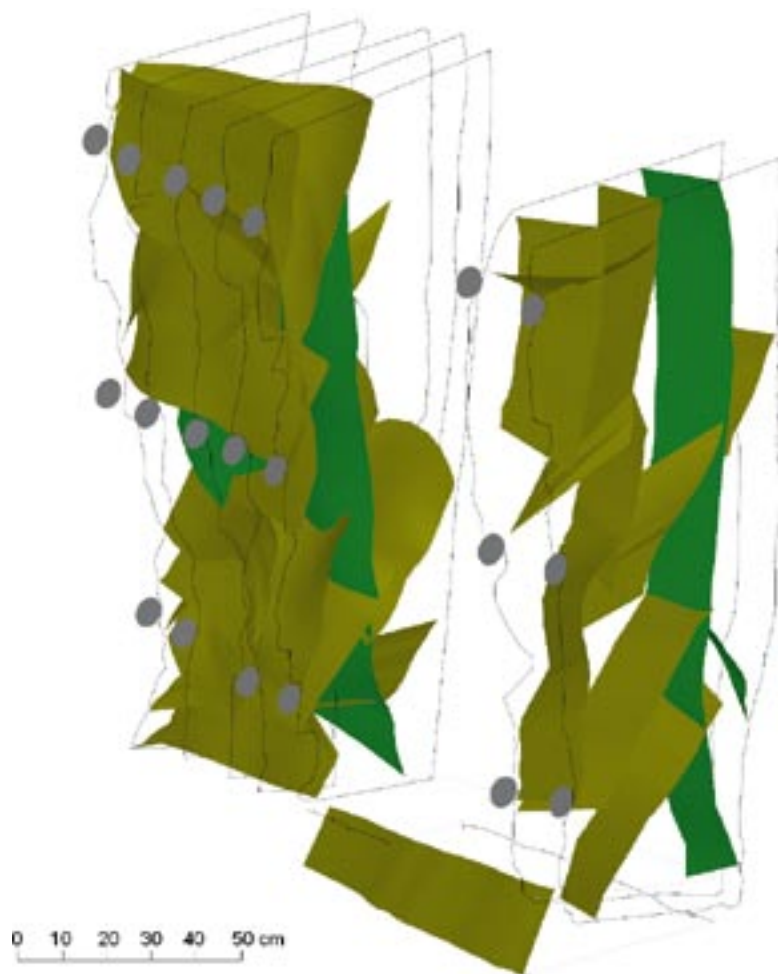
Figure 2-18. *The complete model created. Fractures interpreted as blast induced in yellow and natural fractures in green.*

Test section 2

In test section 2, 17 fractures were modelled which were interpreted as blast induced fractures. Two fractures, interpreted as natural fractures, were also modelled. Four drill-pipes affect the evaluated rock slabs, called A to D from top to bottom. The modelled fractures are named A, B, C and D after the drill-pipe from which they extend. The natural fractures are named N.

2 fractures originate from drill-pipe A, 5 fractures from drill-pipe B, 6 from drill-pipe C, 4 from drill-pipe D and 2 are interpreted as natural fractures.
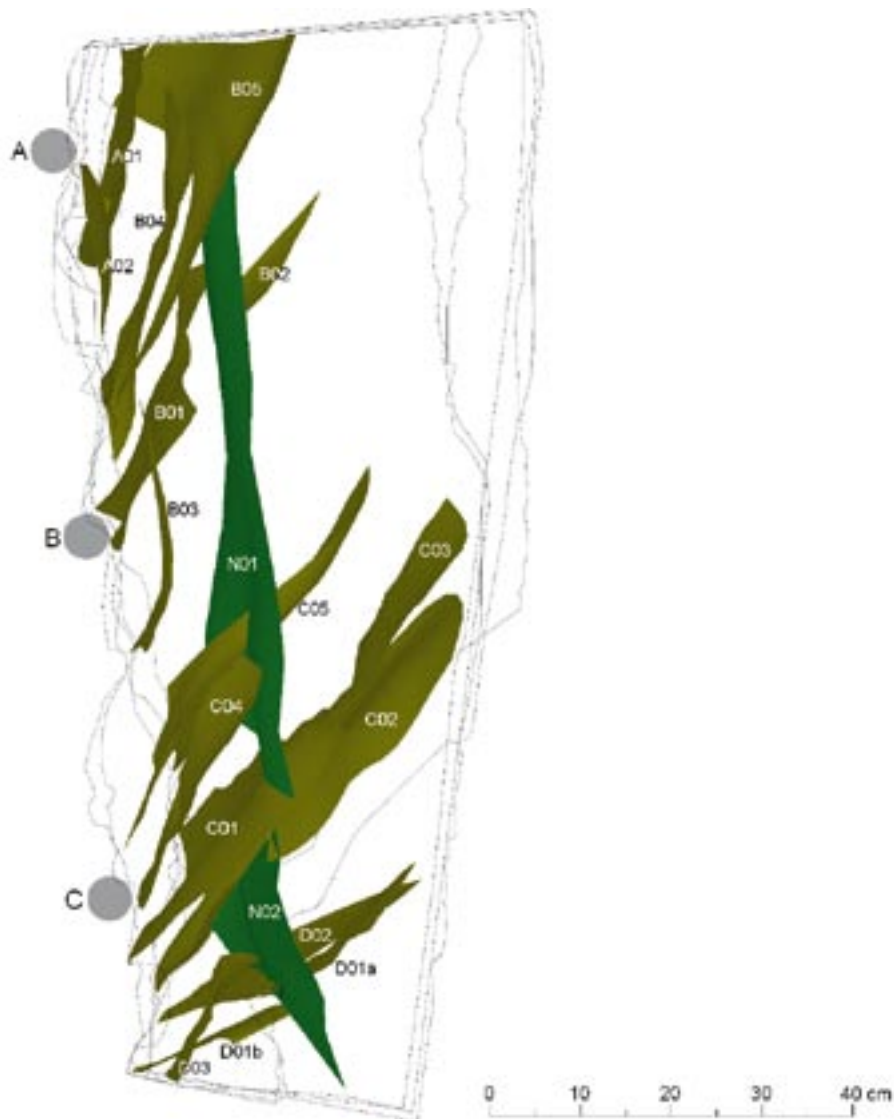
Figure 2-19. *Side view of all modelled fractures in test section 2.*

Test section 3

In test section 3 there were only two sections to connect, hence there were fewer fractures. Here we modelled 9 fractures which were interpreted as blast induced and 2 fractures interpreted as natural fractures. Of the blast induced fractures, 1 fracture originates from drill-pipe A, 2 from drill-pipe B, 5 from drill-pipe C and 1 from drill-pipe D.
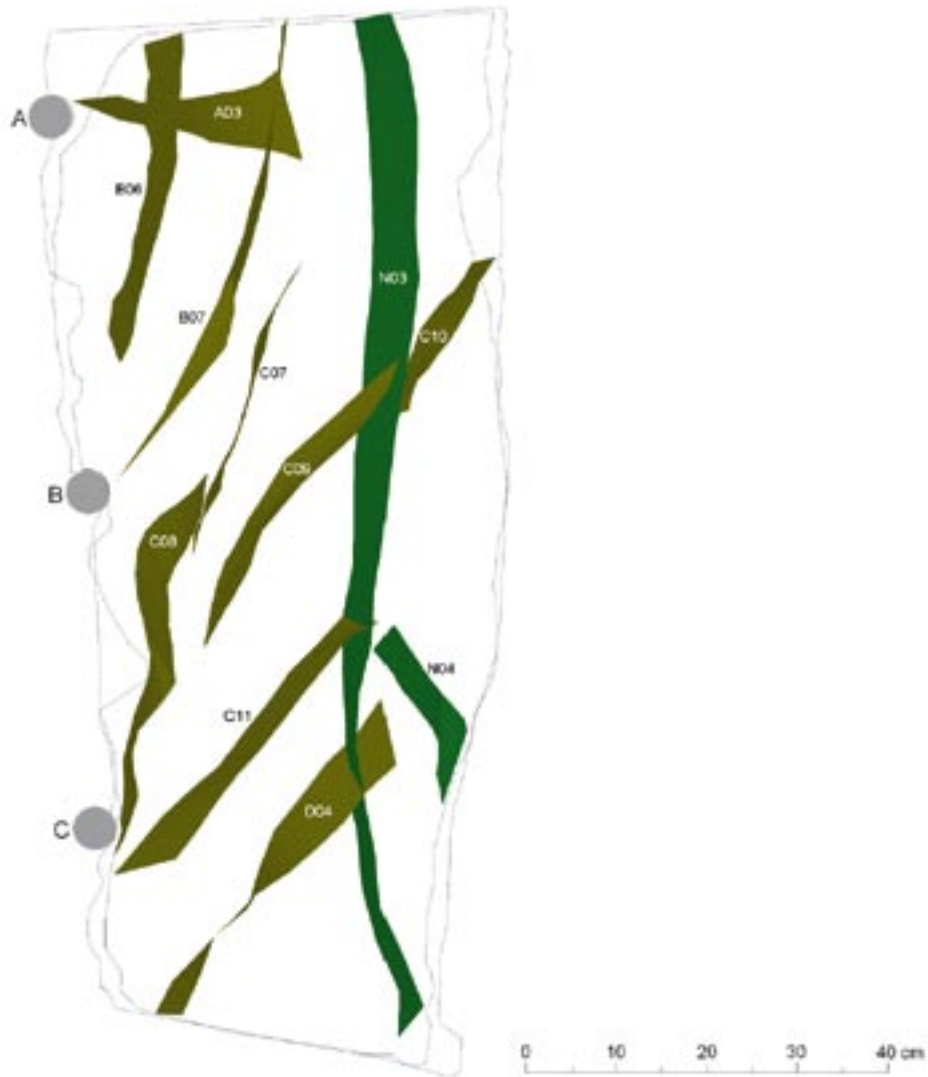
Figure 2-20. *Side view of all modelled fractures in test section 3.*

In one of the sections, a distinct fracture trace could be observed that was not visible in the other section. Hence, it is believed that this fracture stops between the two sections and probably propagates away from the other section. Consequently, this fracture could not be modelled.

Horizontal slot

As mentioned earlier, the condition of the horizontal cutting was not good. The rock slab could not be found and the upper cutting surface was covered with oxidations. Only one fracture could be observed in both sections, a fracture trace parallel to the tunnel wall in the upper section was connected to the outline of the lower section forming a fracture that coincides with the tunnel wall below the slot.

This fracture is probably the same as a fracture modelled in test section 2. Even though they are detected in different places and modelled completely separately, with no common facture traces, they fit exactly in strike and dip.

The fracture clearly terminates against an intersecting fracture, shortly before test section 3 and is hence not visible in the section in test section 3 closest to the horizontal slot. This can be taken as an indication of that the fracture's lateral extent is limited.

Figure 2-21. *The fracture modelled in the horizontal slot, D05(H), shown together with one of the fractures from test section 2, D05(A).*

3   Experiences

3.1   Field investigations

Some examples of experiences from the field work are listed below.

3.1.1   Slots in the tunnel

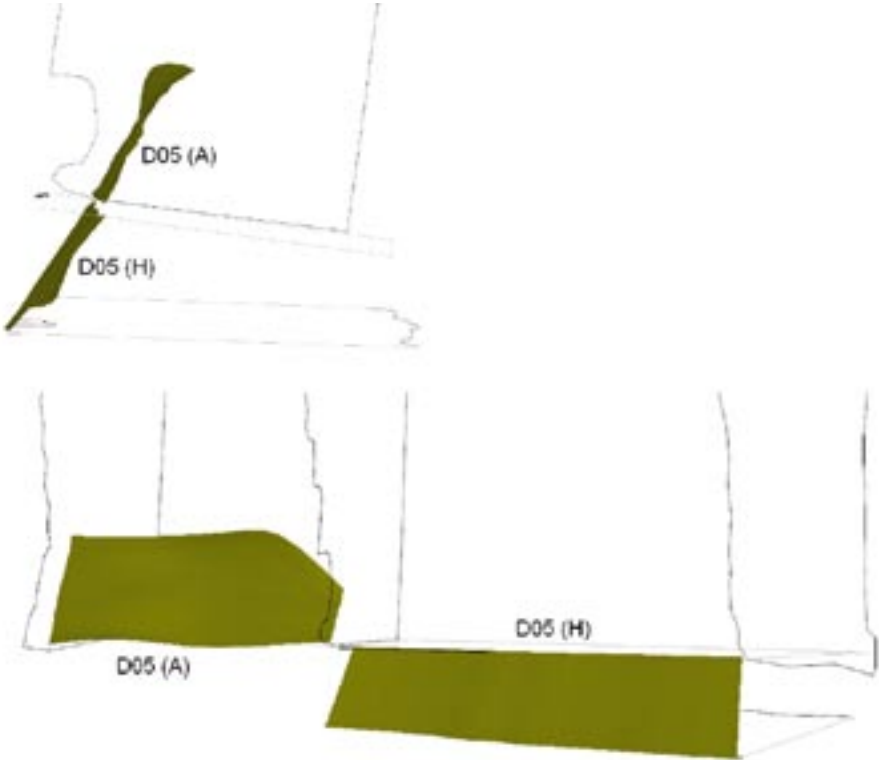• It was very hard to clean the fractures in the slots. These fractures were coloured from the earlier use of the penetrant.

• It was not easy to keep the slot surfaces free from water. The surfaces have to be very dry in order to use penetrants. During this investigation water was also dripping from the tunnel roof, making it harder to place the camera at the best location.

• In the tunnel there was no possibility to take the photograph perpendicular to the rock surface. This means that the images need to rectified before they could be used.

• Another problem was that there was not enough light to have a high enough shutter speed to ensure that camera shake did not show on the images. Hence, multiple images, around 5–15 at a time, were taken to make sure that we got at least one useful image.

• The camera optics should be one with a minimum of optical distortion. However, with the very limited space in the tunnels it is most likely that a wide angle lens will also be needed. A personal preference is around 17 mm on a 35 mm camera as wide angle.

• The use of a tripod is needed to guarantee good images, and a sturdy platform is needed to have support for the tripod.

• It was not possible to use penetrants on the horizontal slot as the surfaces of this slot were partly dirty and partly covered with rust.

3.1.2   Slabs

In the wash hall, where we did the work with the rock slabs, the working conditions were much better than in the tunnel. There was enough light and it was dry.

Some experiences are listed below.

• Problems to identify slabs due to indistinct markings from the old investigations.

• Problems to identify the pieces of the broken slabs.

• The slabs were rather heavy to handle and risked breaking-up when handled.

• It should be enough just to use one side of a slab to identify fractures but to assure a good result both sides should be photographed.

• Developer gives better contrast but also masks fine features and features that have not absorbed enough penetrant.

• The penetrant colours everything red so surrounding areas must be covered for protection.

• The lighting on the slab needs to be as even as possible. Therefore you need to use more than one light. The project used five lights to get a good result.

3.2 Rectification

3.2.1 From the slots

The result of the images from the slots in the tunnel was good and after rectification it was easy to identify fractures.

It would have been better if the rectification points had been measured with a total station to have a better geometry to rectify. This would also mean the images would be automatically placed at the right place in the 3D representation of the tunnel.

When a rectification grid is created it should consist of at least of 6 points.

3.2.2 From the slabs

The result of the images from the slabs in the wash hall was good. They did not need rectification and it was easy to identify fractures with good result.

The images taken with the camera mounted in the roof could be orthogonally rectified to compensate for the field of view distortion that is present in the outer parts of the image. However, given the precision in the rest of the workflow there is no way of knowing how much and how to compensate for the radial angle distortion that is present in the edges of the image compared to the centre of the image. In addition, it is considered that the cost involved in achieving the amount of precision needed to make an orthogonal rectification meaningful is unjustified.

If a lens with a known optical distortion is used, the image should be rectified for that.

3.3 Vectorization

One general problem is that cameras only capture contrast. So no contrast means no fracture. This becomes a problem when the fractures are sealed and accept only a very small amount of dye penetrant. The fractures can be visible to the naked eye but they get lost in the image because they have a contrast very close to that of the background. The only possibility to find the fracture in the image is to look closely at 100% magnification.

The problem is worsened by the crystallization of the rock itself, which on an image can look like a fracture. This makes it harder to assess what should be in the final product and what should be discarded from the image.

The next problem is a product of the first.

When a machine finds and creates vectors from an image the most common method is by finding differences in contrast. This usually means that the difference in contrast needs to be exaggerated and a threshold of what is considered a fracture and what is not needs to be set. As a result there will be a loss of data. The fractures that do not have enough contrast to stand out from the background are eliminated in the process. If these fractures are considered to be important, then this way of automatic fracture finding cannot be used at all.

The programs that we have used require that the images are classified into black and white, where black is considered as a feature and white as the background. In the process of producing this black and white image, most of the finer details are discarded. Like fine fractures, the end of fractures and fractures with a low contrast area in the middle are divided into two separate features.

Areas with a large amount of small fractures will absorb a large amount of penetrant and make an area of high contrast. This means that the individual fractures in that area will have a low relative contrast against the high contrast background and will disappear when the image is prepared for automation. Such areas will be classified as areas of unknown content.

One of the dangers with this methodology is that the result of this contrast enhancement, classification and automation will appear to be very good. There will be little place for doubts or uncertainty in the finished product. But the result may not be that close to reality.

When comparison is made with a manual assessment and classification of fractures, it was concluded that the vector product, after an automated process, may miss important fractures and that the resulting pattern may be dominated by relatively unimportant fractures.

The conclusion is that there are ways to do a manual assessment of the images that dramatically increases the value of the finished product without significantly increasing the amount of time spent on assessment.

3.4   3D transformation

The 3D fitting would be a lot easier and more accurate if the side of a slab to be investigated was equipped with fixed point markers that were surveyed before the slab was excavated. This is described in Chapter 5 below.

It would also be advantageous if modelled surfaces from the laser scanning suitable for use in CAD were available. This must be investigated and is best made when purchasing the laser investigation. It is then vital to check that the delivered meshes are directly usable in RVS/MicroStation.

For the 3D fitting it would be advantageous if the rock wall had been laser scanned both before and after the excavation of the rock slabs, with fix points on both the rock wall and on the parts that will be rock slabs.

It would also be beneficial if the identified drill pipes were better marked, with better precision, during the field investigations, a method to achieve this need to be developed.

When moving from the vectorization to 3D space, all sections in test section 2 had to be scaled, this was another source of inaccuracy. This can, however, be avoided if the correct scale is used when vectorizing, which was proved in the later work with test section 3 and the horizontal slot.

3.5   3D modelling

3.5.1   Modelling

When modelling in 3D the complex geometries mean there are always a lot of different possibilities to connect the fracture traces. Hence, it is important to classify the fracture traces. A visual comparison between the sections, recognizing the fracture pattern, helps when following a fracture from one section to another. There is also always a risk when modelling to "over interpret" and try to find connections for fracture traces between all investigated sections. This can result in an overestimation of fracture persistence. It is important that the modeller instead tries to decide when a fracture actually ends. It is also important to continuously review the original photos as reference, not to miss any data.

When a number of small fracture traces in a section are connected and together act as one continuous fracture, they should be connected into one fracture trace in the interpretation and vectorization, see Chapter 5.5 for guidelines. This must be solved from case to case and is a part of the interpretation work. When the fractures are interpreted and connected, they should also be coded after their properties, to simplify the 3D modelling, see Chapter 5.5.

It is important to acknowledge that the model created is not a completely true representation of the fractures in 3D space, but is rather an image of a possible fracture network, thus increasing the understanding of the geometry of the blast induced fractures.

3.5.2 Data density

When investigating the difference between fracture traces found on opposing sides of the saw cuts (i.e. sections c. 1 cm apart), it was concluded that only a handful (3–5), small fractures were not found from one side to the other. Those fractures were less than 5 cm long and far smaller than the fractures used when modelling. In two different cases, one longer fracture was not found on opposing sides of the saw cut. However, these were not longer than 10 cm and one reason they were not found is believed to be the poor condition of the slabs. Hence, it is safe to conclude that it is sufficient to investigate only one side of each saw cut for modelling purposes. The opposite side could, however, be photographed and viewed as reference.

The slabs in this investigation are approximately 10 cm thick. When investigating the opposing sides of a slab (i.e. sections c. 10 cm apart), it was found that one fracture of c. 25 cm, 2 fractures of c. 15 cm, 2 fractures of c. 10 cm and more than 30 fractures of c. 5 cm or less were not visible from one side to another or vice versa. This implies that the most of the important fractures could be identified from one side of a slab to another. Thinner slabs would not add much information and would also be hard to handle without risking breakages.

Investigating the difference spanning two slab thicknesses (i.e. sections c. 20 cm apart) is more difficult, since it is hard to identify which fracture is which. The fracture pattern is the same, but if it actually is the same fractures or simply a similar fracture pattern is very hard to determine when you investigate two sections so far apart. Furthermore, to be able to connect fractures into fracture planes with any level of confidence, you need to see the fracture in three sections or more, which is difficult when the sections are too far apart.

Hence, it is concluded that a slab thickness of 10 cm could be recommended for future investigations.

4   Conclusions and recommendations

It is possible to visualize fractures from photos in a CAD-model. It is also possible to connect fractures and generating 3D planes. However, there are some important factors to consider:

Before the sawing of the slabs the tunnel has to be surveyed by laser scanning or/and total station.

The fractures on the rock walls should be mapped in detail; this would add valuable information and make the 3D interpretation easier.

Slab thicknesses of 10 cm are recommended for future investigations.

Before the slabs are removed they must be marked to facilitate the rectification. It is, however, important that nothing is written on a surface that is to be photographed. It obscures potentially important information and costs unnecessary time to remove from the images.

Before the removal of a slab its position must be measured by surveying fixed point markers on the side to be investigated, six markers are recommended.

The removal of slabs has to be performed very carefully in order to prevent them breaking up.

The slabs must also be marked directly after removal to make sure that all pieces are accounted for and easy to find when it is time to photograph them.

It is very important to keep the surfaces of the slots free from water leakage.

It is sufficient to investigate only one side of each saw cut for modelling purposes. The opposite side could, however, be photographed and viewed as reference. The investigated side should have the surveyed fixed points.

It would be beneficial to have all the slabs placed in a specific position in accordance to the bore pipes or another feature that are present on all slabs.

It is important to use developer to intensify the contrast of the photos.

The automatic vectorization is fast but the need for manual handling of the data to make it useful for further work does mean that there are no convincing benefits from the automation. A method that would work better for vectorization is screen digitizing the fractures using a program that can display the image and is able to pan and zoom in the image. The user draws the vectors on the screen where he finds fractures. For each feature the user should enter a classification along with other information, see Chapter 5.5. Using this method the user can track fractures between the layers and make a first assumption about which fractures connect between the layers and add that information when digitizing fractures.

For each fracture trace to be connected to another fracture trace in 3D it is very important to be aware that there are many different ways to connect fractures to 3D plans. In Chapter 5.7.2 some guidelines are given for the 3D modelling.

The modeller should be aware of the risk of "over interpretation" and not try to always connect all fracture traces between sections. Instead, it is important that the modeller tries to decide when a fracture actually ends.

The easiest fractures to connect into 3D planes seem to be the natural fractures. In this investigation the majority of the blast fractures had the same upward direction. This is probably due to the stress situation in the tunnel wall.

When modelling with better data, a level of confidence should be set on the modelled fractures, see Chapter 5.7.2 for guidelines.

In a new modelling step with better data, other typical fractures (like sealed natural fractures) should be included when they can be seen interacting with or cutting off the modelled fractures.

A distinct fracture trace that cannot be found in more than one section cannot be modelled in 3D.

Even if it is possible to model a network in 3D, it must be acknowledged that it is not a completely true model of the fractures in 3D space; it is rather an image of a possible fracture network.

Use up-to-date cameras and proper lighting to make first class pictures. Also, if the current rate of camera development is maintained we will in a near future have cameras that have the possibility to take images with higher resolution and more dynamic range, enabling us to have even higher magnification of the fractures.

The market for new dye penetrants that have better penetration properties and that bleed less should be closely followed.

5   Step-by-step

Below, all recommendations for future investigations are listed step-by-step for each stage in the investigation.

5.1   Field work

• Be sure to have all the drilling and blasting plans.

• Select suitable area. There must be visible half pipes.

• Do a full survey, including laser scanning and surveying of fix points and bore pipes.

• Document the area by photos, both overview and interesting details.

• The sawing must be performed carefully, a slab thickness of 10 cm is recommended.

• Before starting to loosen the slabs the front edge of the slabs must be marked and the position of the slabs must be surveyed with a total station.

• When a slab is removed, the slot surface that will be the face of the next slab should be cleaned and measured. At least six fix point markers should be attached to the surface and surveyed with a total station. Also, the surface should be photographed. This is important if the slab breaks into pieces when later removed.

• Handle the slabs with care. If the slabs break the pieces must be marked for identification.

• Document all the loosening by photos.

5.2   Slot investigations

• Clean the surfaces of the slots, keep them free from water. If necessary use drainage saw cuts

• Use warm air fans to dry the surfaces (fans and heat guns).

• Attach markers (for rectification) on the cleaned surface, at least six, and survey their position with a total station).

• Write some number identification on the side of the slots.

• Position sufficient amount of light to get an even light over the whole surface that will be photographed, in order to get a fast enough shutter time to ensure that no camera movement is visible in the image while keeping the lens at its sharpest f-value.

• Put on the dye penetrant and let it work for 10–15 minutes.

• Wash away the excess and dry again. Make sure that the attached markers still show.

• While drying, position the camera and make a test shot. The bleeding starts to affect the image quality very fast.

• Take initial pictures of the fractures with and without a scale reference.

• Put on the developer and dry the surface quickly. Make sure that the attached markers still show.

• Take a new set of pictures of the surface with and without a scale reference.

5.3   Investigating the slabs

- Careful transportation of the slabs is essential.

- Prepare the location where the photos will be taken. Mount the camera perpendicular to the slab to avoid the need for rectification. Setup the lights. Make sure that there is enough light and that it is evenly spread over the slab. Make sure that the lens field of view can accommodate the largest slab.

- Take some test photos and fine tune the setup.

- Take the first set of photos of the slab with the markers from the tunnel still attached. If the slabs are moved after this step the markers can not be applied to the following images unless they are placed in the exact same place for the following images.

- Be careful to blow dry the slabs free from water. Using some extra time here will give a much better result with less bleeding of penetrants from the fractures. A good way would be to dry the slabs in an oven. This process may be time consuming but will probably end up with more distinct fractures.

- Put on the dye penetrant and let it work for 10–15 minutes.

- Wash away the excess and dry again.

- Take initial pictures of the fractures with and without a scale reference. The scale is very useful when determining distances in the image and for cross-checking of scales but pictures should also taken without the scale since it can obscure.

- Apply the developer, make sure that it is applied as evenly as possible, and dry the surface quickly.

- Take photos of the surface with and without a scale reference.

5.4   Rectification

- Create a backup of the originals so a copy of an unaltered original always exists.

- Apply lens correction if needed.

- Assess the images and make sure they are as sharp as possible and that the black and white points are optimal.

- Adjust the contrast to make sure that the fractures are as visible as possible.

- Setup the program of choice.

- Load the image and the rectification points.

- Apply points to image. At least 6 points.

- Apply triangulation rectification.

5.5   Vectorization

- Add a georeference to the images to give them the proper scale and position in 3D space. If the vectorization is done with a 2D tool, this step can be done when moving into 3D space, see below.

- Stack the images in the correct order in the program that will be used for the assessment. The stacking means that the user can flip through the layers and see what is directly beneath and above the current location on the image. If available both sides of the slabs should be entered.

- Create the different layers that will be used to store the vectors.

- Start the assessment.

- Create new vectors for the interpreted fractures. When one fracture is done the user should record information about the feature he just created. This information should be a classification of fractures as Natural, Blast or Blast Induced fractures. For natural fractures, observed features like fracture minerals, oxidation and open or closed should be entered. The information should also, when possible, include details about which features on the different layers the assessor believes to connect into a surface in 3D space.

- When vectorizing, gaps in fracture traces, smaller than c. 2 cm can be closed and the fracture traces connected into one longer fracture trace. This can be done if the fracture traces are judged to interact, based on observations of the same fracture(s) in adjacent investigated sections.

5.6   3D transformation

- Set up an RVS model in 3D space.

- Attach each section file as a reference to the RVS model. One section side per slab plus the slot sides. Use the sides with surveyed fix points (see above).

- If the sections are not already georeferenced, orientate and move each scanned section to the correct place in 3D space using the surveyed points.

5.7   3D modelling

- Review the vectorized sections and try to fit fracture traces between sections geometrically. Consider any properties or classification entered when vectorizing, see Chapter 5.5.

- Connect the selected fracture traces to form undulating, modelled fracure planes using the RVS modelling function *Surface by Profiles,* which connects selected line strings to a surface, spanning the area between the line strings without extrapolation.

- For each created fracture, enter confidence, see Chapter 5.7.2 for guidelines.

- Review the fracture network created and cut fractures to each other if needed.

- When modelling, continuously review the original photos as reference. Do not only use the vectorized sections, data can be missed.

5.7.1 Recommended guidelines for modelling

Generally it is difficult to set up objective criteria to connect fracture traces. It is very much up to the experience of the modeller in charge.

However a list of potential criteria for consideration is presented below:

General, all fracture types

- Fracture length: A fracture with a trace length longer than the section spacing should be possible to identify in surrounding sections. Shorter traces should only be used if they are judged to be the end part of a larger fracture modelled in an adjacent section.

- Fracture orientation: Fracture traces to be connected should have the same general orientation in adjacent sections.

- Fracture trace position: Modelled fractures should form semi-planar fracture planes.
  If a fracture bends or undulates to form a wavy pattern, it can be assumed that it is a swarm of parallel fractures, not necessarily connected.

Blast fractures, specific

- Fracture origin: Blast fractures to be connected between sections should originate from the same blast hole.

Natural fractures, specific

Fracture properties: Coincident fillings, minerals and/or oxidation, open or closed.

5.7.2 Recommended guidelines for confidence classification

The level of confidence of a modelled fracture depends on how many sections the fracture is observed in and if the lateral extent of the fracture can be validated by any observation of perpendicular fracture traces e.g. surface mapping of the tunnel wall or excavated rock block.

Table 5-1. Suggested confidence classes

Confidence class	Description
3) High	Identified in at least 5 sections **or** in at least 3 sections in combination with supportive information in a perpendicular section. Similar appearance in all sections. Forming semi-planar fracture planes.
2) Medium	Identified in at least 3 sections. Similar appearance in all sections. Forming semi-planar fracture planes.
1) Low	Identified in less than 3 sections. Fairly similar appearance in both sections.

6 Future development

An interesting future development would be to develop a new technique to investigate and take photos of the surface inside a single saw cut without excavating the slabs. The technique could include both photos and other scanning methods to detect fractures in the rock surface. A good idea would be to start a smaller project as a pilot study to examine suitable techniques. There are two tracks to follow.

The first and most likely to work is optical scanning, meaning taking images that are suitable for human assessment.

The way that seems most possible is to use fibre optics, like the ones commonly used by the police, medical service and in the construction industry. This could be modified by placing a prism at the end of it to bend the optics at a 90 degree angle.

This would enable the fitting such optics to a camera that could be placed outside of the saw cut thus enabling the use of bigger components than the 5 mm cut otherwise would allow. And by using another fibre core to lead the light into the saw cut the light source needed to take the photo can also be placed out side the saw cut, enabling the use of an inexpensive strong light source without having to worry about size or heat emissions.

This device could be mounted in a frame that would be used to move the device around and make it work like mix between a flatbed scanner and an old fashion plotter. After fixing the frame, a couple of points on the frame would be measured with a total station, thus enabling each pixel to be given a coordinate in 3D space.

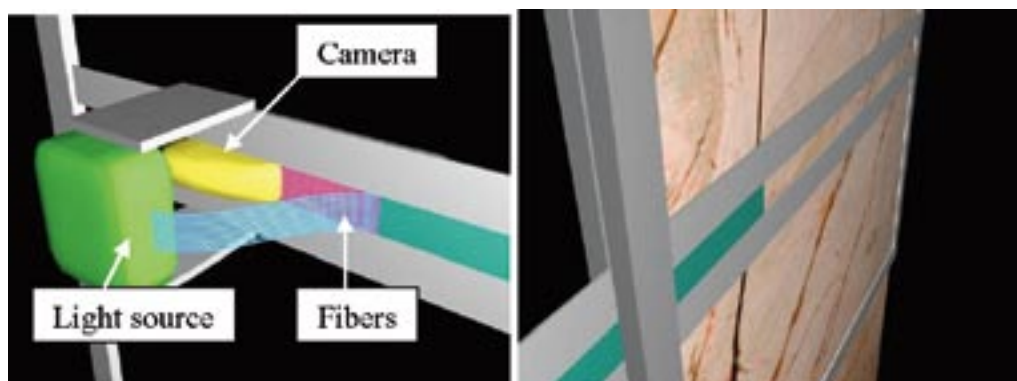***Figure 6-1.*** *Hypothetical design of a scanning device showing the parts inside the slot.*

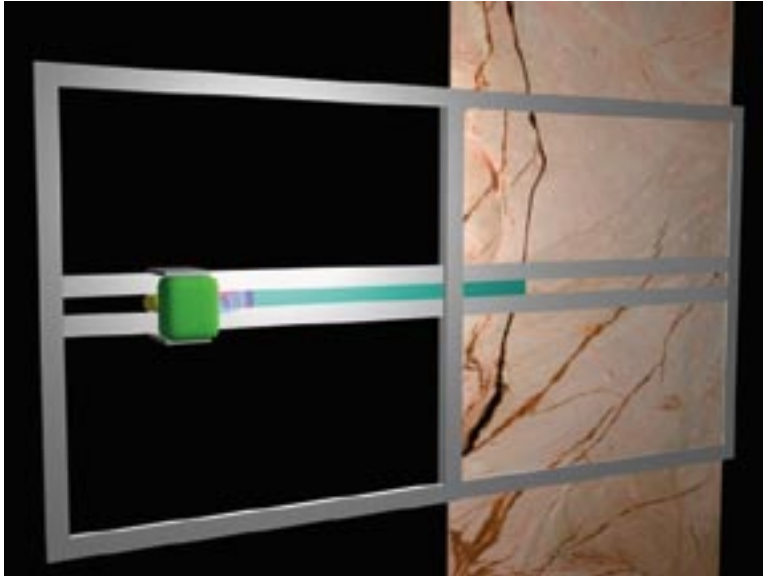***Figure 6-2.*** *Hypothetical design of a scanning device, showing the parts outside the slot.*

Figure 6-3. *Hypothetical design of a scanning device, showing the entire device.*

The other method of scanning the rock is by some sort of "radar". The word radar is used here more as an abstract concept then as a way to describe a certain technique.

The reason for exploring such a technique is that the scanning would be cheaper than removing slabs from the side of the tunnel and thus it would be possible to take more images for less money. However, more images will mean that the assessment process will consume more time and more personnel. With a technique like the one described below the increased amount of information would not lead to the same increase in man hours needed.

The goal of the technique is to "feel" the fracture when the reader scans the rock surface. The end product would be a map showing the possible fractures with an accuracy of at least 80%, meaning that if the same surface is scanned five times the device will pickup the fracture at least four times. This used as an overlay on an optical image of the rock surface would decrease the workload of the person doing the assessment.

The preliminary investigation shows that it might be hard to find a technique that works in the conditions prevailing in a tunnel. Also, the small sizes of the fractures that need to be detected mean that the frequency is very high making it hard to handle. The size of the device is also a problem as it is intended for use in narrow saw cuts.

These issues taken together make it unlikely that a project might come up with a working device, but new techniques are being developed all the time so it is not impossible that one will be available in the future.

In order to investigate the feasibility of this technique further, a separate project needs to be initiated. The first step would be to set up a project plan defining stepwise investigations including desktop studies, investigations in lab, investigations in the field and finally a full-scale test. After each step there would be a control point where it should be determined if the results are promising enough to continue to the next step.

7   References

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