BLAST-INDUCED DAMAGE
A SUMMARY OF SVEBEFO INVESTIGATIONS

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SUMMARY

This report presents a summary of the blast damage investigation carried out by SveBeFo (Swedish Rock Engineering Research) during the period 1991 to 2003 at various hard rock sites in Sweden. The objective of this report is to present a synopsis of the important factors that influence the development and extent of the blast-induced damage zone, nature and characteristics of blast-induced fractures, and a summary of the blast-damage thickness with reference to the existing perimeter blasting damage guidelines for tunnelling and drifting practices in Sweden. Ultimately this report will assist the author in developing numerical models to study the effects of blast-induced damaged zone on stability parameters. It has to be stated clearly that this report is intended as summary and not a reproduction of the works of SveBeFo. It may not also represent the actual conclusions or views of SveBeFo in areas where this author attempted to interpret and conclude from some of the data. Interested readers are strongly urged to consult the SveBeFo publications referenced in this report.

The SveBeFo blast damage investigations during the period 1991 to 2003 were carried out at three principle hard rock sites: (i) Vånga granite quarry, (ii) LKAB’s Malmberget and Kiruna mines and (iii) SKB’s TASQ tunnel. The primary goal of these studies was to improve perimeter blasting guidelines for tunnelling and drifting in hard rock masses in Sweden. Within this scope were several objectives such as: (i) to develop guidelines for blast-induced damage control for drifting and tunnelling in hard rock masses, (ii) devise method for blast damage assessment, (iii) verification of the devised methods in tunnelling and drifting sites.

Generally used perimeter blasting techniques, particularly smooth blasting, were employed in the tests. Multiple holes of different, but commonly used, diameters for perimeter holes were used. The explosives used were those commonly used for tunnelling and drifting. After the blasts saw cuts were extracted from the remaining rock, cut into manageable sizes, sprayed with penetrants (to make the blast-induced cracks traceable or visible) and crack parameters (length, quantity and pattern) investigated.

The size and pattern of blast-induced damage were observed to depend on various parameters, namely; explosive parameters (explosive type, charge length, initiation method and coupling), blast hole pattern (burden, spacing and hole diameter), in-situ rock mass parameters (geology, in-situ stress, and rock strength and stiffness) and
water in the holes. The thickness of the observed damage ranged between 0.1 and 1.2 m. An average damage thickness of 0.5 m was observed in the Kiruna and Malmberget mine drifts and 0.3 m in SKB’s ÄSPE/TASQ tunnel and Vånga granite quarry.
ACKNOWLEDGEMENT

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1. INTRODUCTION

Between 1991 and 2003 SveBeFo (Swedish Rock Engineering Research) carried out extensive field investigations to measure and predict the extent of blast-induced cracks. The main objective was to obtain a basis for improved contour blasting of tunnels. Details of these investigations can be found in a series of SveBeFo reports; Andersson (1992), Olsson & Bergqvist (1993), Olsson & Bergqvist (1995), Fjellborg & Olsson (1996), Olsson & Bergqvist (1997), Olsson et al (2002) and Olsson & Ouchterlony (2003). These tests were mainly conducted under controlled conditions at four principle sites: (i) the Vånga granite quarry, (ii) LKAB’s Malmberget mine (iii) LKAB’s Kiruna mine and (iv) SKB’s TASQ tunnel at ÄSPÖ. Figure 1 shows these sites. The cautious contour blasting techniques were used. The explosives used during the tests were those commonly used in perimeter blasting.

The Vånga dimension quarry was the core site for the blast damage investigations. Here, tests were conducted under carefully controlled conditions. Saw cuts were extracted and crack mapping performed, both in the field and in the laboratory. The Vånga tests led to: (i) identification of important parameters that affect the development and extent of blast-induced cracks, (ii) development of a systematic method for blast damage mapping and assessment and (iii) formulation of an equation to predict blast-induced crack lengths resulting from cautious blasting.

LKAB’s Kiruna and Malmberget mine, and SKB’s TASQ tunnel served as sites for testing and verification of the knowledge gained and methods devised from the Vånga dimension stone quarry experiments. Tests at LKAB’s Kiruna and Malmberget mine also had two other objectives: (i) verification of the SveBeFo methods against vibration based models of Holmberg & Persson (1980) and Hustrulid et al (1992), and (ii) to test the possibility of increasing the advance while keeping the blast-induced damage as minimum as possible. Tests along a 70 m segment of SKB’s TASQ tunnel was intended to provide information on how to control blast-induced damage during the development of the rest of the tunnel. Since the primary objective of the TASQ tunnel was for rock mechanics studies, it was intentionally oriented to permit high horizontal stresses to act perpendicular to the tunnel axis. This also provided an opportunity to study the effects of high in-situ stress on the development and extent of blast-induced cracks.
In all of the verification tests sites, saw cuts were extracted and systematic damage mapping were performed. Overbreak profiling, vibration measurements and borehole camera logging were also performed at the verification sites.

It was found that the size and depth of blast-induced cracks depended on various parameters, namely; explosive parameters (explosive type, charge length, initiation method, coupling), drill hole parameters (burden, spacing and hole diameter) and in-situ rock mass parameters (geology, in-situ stress, rock strength and stiffness). The assessed depth of the damaged zone ranged between 0.2 – 1.2 m.

This report presents a summary of the SveBeFo investigation on blast damage at the four principle sites. The main focus, however, is about the geometrical properties of the blast-induced damage zone and the factors that affect these properties. For other details interested readers are urged to consult the relevant SveBeFo reports referenced herein.
2. BACKGROUND

For more than two decades a table, such as Table 1 or in chart form as in Figure 2, was used in Sweden for estimating damage due to blasting during tunnelling and drifting (e.g. Olsson and Ouchterlony, 2003; Ouchterlony et al., 2001). Commonly used explosives for these works are usually listed in order of their linear charge concentration in terms of kg Dynamex per meter as in Table 1. However, the table suffers from many shortcomings and has only been verified for a couple of explosives under specific circumstances (Olsson and Ouchterlony, 2003). For instance, the table does not take into consideration the influence of blast hole pattern, scatter in initiation, coupling ratio, and furthermore does not provide a clear definition for blast-induced damage. Nevertheless the table has been a practical tool in designing perimeter blasting in hard rock masses in Sweden.

Table 1: Empirical damaged zone table for tunnel blasting from commonly used explosives applied to 45 – 51 mm diameter holes (AnläggningsAMA-98, 1999)

<table>
<thead>
<tr>
<th>Explosive type</th>
<th>Charge diameter (mm)</th>
<th>Charge concentration (kg DxM/m)</th>
<th>Assessed damaged zone thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detonex 40</td>
<td>0.04</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Gurit A</td>
<td>17</td>
<td>0.17</td>
<td>0.3</td>
</tr>
<tr>
<td>Detonex 80</td>
<td>0.08</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Emulet 20</td>
<td>45</td>
<td>0.22</td>
<td>0.4</td>
</tr>
<tr>
<td>Gurit A</td>
<td>22</td>
<td>0.30</td>
<td>0.5</td>
</tr>
<tr>
<td>Kimulux 42</td>
<td>22</td>
<td>0.41</td>
<td>0.7</td>
</tr>
<tr>
<td>Emulet 30</td>
<td>45</td>
<td>0.37</td>
<td>0.7</td>
</tr>
<tr>
<td>Emulite 100</td>
<td>25</td>
<td>0.45</td>
<td>0.8</td>
</tr>
<tr>
<td>Emulite 150</td>
<td>25</td>
<td>0.55</td>
<td>1.0</td>
</tr>
<tr>
<td>Emulet 50</td>
<td>45</td>
<td>0.62</td>
<td>1.1</td>
</tr>
<tr>
<td>Dynamex M</td>
<td>25</td>
<td>0.67</td>
<td>1.1</td>
</tr>
<tr>
<td>Emulite 100</td>
<td>29</td>
<td>0.60</td>
<td>1.1</td>
</tr>
<tr>
<td>Emulite 150</td>
<td>29</td>
<td>0.74</td>
<td>1.2</td>
</tr>
<tr>
<td>Emulite 100</td>
<td>32</td>
<td>0.74</td>
<td>1.2</td>
</tr>
<tr>
<td>Emulite 150</td>
<td>32</td>
<td>0.91</td>
<td>1.3</td>
</tr>
<tr>
<td>Dynamex M</td>
<td>29</td>
<td>0.88</td>
<td>1.3</td>
</tr>
<tr>
<td>Dynamex M</td>
<td>32</td>
<td>1.08</td>
<td>1.5</td>
</tr>
<tr>
<td>Prillit A</td>
<td>45</td>
<td>1.23</td>
<td>1.6</td>
</tr>
<tr>
<td>Emulite 150</td>
<td>39</td>
<td>1.30</td>
<td>1.7</td>
</tr>
<tr>
<td>Prillit A</td>
<td>51</td>
<td>1.58</td>
<td>2.0</td>
</tr>
<tr>
<td>Dynamex M</td>
<td>39</td>
<td>1.60</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Between 1991 and 1996 SveBeFo conducted a series of blast-damage investigation at Vånga dimension stone quarry in southern Sweden (see Figure 1). One of the main aims of this study was to improve Table 1. This work led to 3 main outcomes: (i) a method for blast-induced damage investigation (Olsson and Bergqvist, 1995; Olsson and Bergqvist, 1997), (ii) identification of important parameters that affect the development and extent of blast-induced damage (Olsson and Bergqvist, 1995; Olsson and Bergqvist, 1997; Olsson et al., 2002) and (iii) a new formula for predicting the extent of blast-induced cracks resulting from cautious blasting (Olsson and Ouchterlony, 2003; Ouchterlony, 1997a; Ouchterlony, 1997b). The new formula takes into consideration some of the important parameters that affect the development and extent of blast-induced cracks.

The knowledge gained and techniques developed from Vånga were later used to investigate blast-induced damage at LKAB’s Kiruna and Malmberget mines in northern Sweden and SKB’s TASQ tunnel in southern Sweden (see Figure 1). These tests also served as verifications of the techniques developed at Vånga. Despite some practical difficulties the methods were verified and considered to be successful.
3. THE VÅNGA QUARRY BLAST DAMAGE INVESTIGATION

3.1 Summary of test procedures

Field studies were conducted at Vånga dimension stone quarry to study crack propagation from multiple hole blasting under different but carefully controlled conditions. The Vånga quarry (see Figure 3) comprised of hard granite of good quality, with compressive and tensile strengths of 200 MPa and 12 MPa respectively. Tests were carried out in 5 m benches and a total of about 230 small diameter holes of 38 mm, 51 mm and 64 mm were drilled and blasted.

In order to study the influence of drill pattern on crack propagation, burdens of 0.5 m to 0.8 m were tested (e.g. Figure 4). The holes were charged up to 0.5 m from the collar with different types of explosives that are commonly used in perimeter blasting. Furthermore, for some tests the blast holes were coupled with column charges. To achieve exact initiation when firing instantaneously and controlled initiation times in other cases, electronic detonators from Nitro Nobel were used. After blasting a row of blast holes, rock blocks were excavated behind these holes, after they had been marked for identification purposes (see Figures 5 and 6). The blocks were then cut by a diamond saw (see Figure 7) across the half casts. A penetrant was then sprayed on the new surface (see Figure 8). Then the cracks created by blasting were studied, with respect to length and number (i.e. quantity).
Figure 3: (a) The Vånga dimension stone quarry (Photo adapted from Olsson & Bergqvist, 1995) and (b) photo showing the quality of the granite (photo: courtesy of Mats Olsson).

Figure 4: Layout of the drill holes (adapted from Olsson & Bergqvist, 1995).
Figure 5: Smooth blasted rock wall marked out and ready for block extraction (photo adapted from Olsson & Bergqvist, 1995).

Figure 6: A block extracted from the smooth blasted bench (photo adapted from Olsson & Bergqvist, 1995).
3.2 Summary of test results

Table 2 and Figure 9 show the maximum crack lengths resulting from the common explosives and charge diameters. These results indicate increase in crack length with
increasing charge. However, a significant reduction in the crack length was observed when decoupled charges were used. An increased number of cracks was observed close to the drill-hole when high VOD explosives were used (see Figure 10). It was also observed that the initiation method was a very important parameter. The best result was obtained when a row of holes was fired instantaneously. This resulted in shorter cracks compared to blasting single of holes. A difference of a few milliseconds in the initiation time between the holes showed a deterioration of the result, i.e. longer cracks develop. For some explosives there was a tendency for the crack lengths to increase when the burden was increased.

Table 2: Maximum observed crack lengths from various explosives and charge diameter (extracted from Olsson & Bergqvist, 1995).

<table>
<thead>
<tr>
<th>Explosive type</th>
<th>Hole diameter (mm)</th>
<th>Charge diameter (mm)</th>
<th>Maximum crack length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gurit 17</td>
<td>51</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>Gurit 22</td>
<td>64</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>Gurit 22</td>
<td>51</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>Kimulux 42</td>
<td>64</td>
<td>22</td>
<td>37</td>
</tr>
<tr>
<td>Emulet 20</td>
<td>51</td>
<td>Bulk</td>
<td>26</td>
</tr>
<tr>
<td>Detonex 80</td>
<td>51</td>
<td>10.6</td>
<td>16</td>
</tr>
</tbody>
</table>

Figure 9: Crack length versus explosive type. Note the charge diameter from Table 2. After Olsson and Bergqvist (1995).
3.3 Crack patterns

Many different and complex fracture patterns were observed by SveBeFo from the bench blasting at Vånga quarry. The different crack patterns observed depended on factors such as; explosive parameters, blast-hole geometry and rock mass properties. Figures 11 to 15 show some examples of the various fracture patterns observed.

Figure 11 shows the crack pattern where Kumulux was the explosive, a large number of short radial cracks close to the hole were observed, with maximum length of about 25 cm.

Figure 12 shows the result when blasting was done with a wider hole spacing, with Gurit as the explosive. The result is the bow-shaped tangential cracks as seen in the figure. The maximum crack length was about 40 cm.

Figure 13 shows the results where the Emulet 20 was the explosive and the holes were completely filled. Long cracks were observed, with maximum length about 55 cm.
Figure 11: Radial cracks observed around $\Phi 64mm$ blast-holes from the bench blast. The explosive used was Kumulux with 22 mm cylindrical column charge, with the holes blasted instantaneously (Olsson and Bergqvist, 1995).

Figure 12: Bow-shaped tangential cracks observed around $\Phi 51mm$ blast-holes from the bench blast with wider hole spacing. The explosive used was Gurit with 22 mm cylindrical column charge (Olsson and Bergqvist, 1995).

Figure 13: Crack patterns observed around $\Phi 51mm$ blast-holes from the bench blast. The explosive used was Emulet 20 with completely filled holes and blasted instantaneously (Olsson and Bergqvist, 1995).
Figure 14 shows the results of a Ø24 mm blast-hole charged with 22 mm Gurit (i.e. column charge). Crack lengths of up to 90 cm was observed.

![Figure 14: Crack patterns observed around Ø24mm blast-holes from the bench blast. The explosive used was Gurit with 22 mm column charge, 20 with completely filled holes and blasted instantaneously (Olsson and Bergqvist, 1995).](image)

3.4 Other features

Pre-existing fractures can either limit or enhance the growth of the blast-induced fractures. Figure 15 for example shows a pre-existing crack inhibiting the growth of blast induced cracks, while Figure 16 is an example of a natural crack enhancing the growth of blast-induced cracks.

![Figure 15: A pre-existing crack running parallel to the blast-holes inhibits the propagation of the blast-induced cracks (photo: courtesy of Mats Olsson).](image)
Figure 16:  Blast-induced crack propagating along pre-existing crack with a favourable orientation (photo: courtesy of Mats Olsson).

4. KIRUNA UNDERGROUND MINE DRIFT TEST

During the period 1997-99 SveBeFo carried out a blast damage project at the Kiruna mine, in co-operation with LKAB, to test models for blast damage estimation around the mine drifts. Details of this work can be found in Nyberg et al (2000b). Saw cuts of approximately 0.5 x 0.5 x 2.0 m (width x length x height) were extracted from across the half casts in the contour to verify the damage (see Figure 17). The tests were carried out at a depth of 750 to 800 m in waste rock and magnetite ore. The waste rock was largely composed of trachyte (internally known syenite porphyry) with a density of 2710 kg/m³ and compressive strength of over 300 MPa. The magnetite ore had density of 4800 kg/m³ and compressive strength of approximately 120 MPa.
4.1 Summary of test procedures

Two types of blast patterns shown in Figures 18 and 19, for magnetite ore and waste rock respectively, were tested in 5 m long rounds. In the ore drift (Figure 19) the boreholes comprised of a single Ø 64 mm cut hole and Ø 48 mm blast holes. For contour holes a column charge of Ø 22 mm were used. The spacing of contour holes were varied from 0.6 m to 1.0 m. Explosives type, coupling ratios (charge diameter/blast-hole diameter) and firing method and sequences were varied during different test rounds.

In the waste rock drift (Figure 19) the diameter of all the boreholes, including the 6 empty cut holes, was 48 mm. For the contour holes a column charge of varying ratios (charge diameter / blast hole diameter) were used. The holes adjacent to the contour holes, generally regarded as “the help holes”, were also decoupled with varying column charge ratios. As in the ore drifts the explosive type, coupling ratios, and the firing method and sequences were varied during different test rounds. Totally over 125 rounds were blasted.
4.2 Summary of results

After spraying with a penetrant, to make the cracks traceable, the blast-induced damage was visually examined. Table 3 shows the thickness of blast-induced damage from the examination of the waste rock saw cuts. The damaged zone extents predicted by the scaling and damping law models are also shown, which in most cases over predict the actual damage, with Gurit Ø 22 mm an exception for the damping law. The observed crack length, induced by blasting, ranges from 0.1 – 0.4 cm, while predictions from the vibration models range from 0.4 – 0.7 m.
In the magnetite ore drift blast induced cracks were difficult to identify visually across the half casts (see Figure 20 (a)). On the other hand intense pattern of cracks were observed in the saw cuts, revealing the dominance of tangential cracks. Lower velocities and higher rock damping were noted across the magnetite ore drifts. Geological mapping of magnetite revealed that the ore was foliated and the dominating stress direction was sub-parallel to the drift.

Table 3: Observed and predicted thickness of blast-induced damage (Nyberg et al., 2000c).

<table>
<thead>
<tr>
<th>Contour hole diameter (mm)</th>
<th>Explosive type and charge diameter (mm)</th>
<th>Observed damage size (m)</th>
<th>Damage size (m) predicted by scaling law (Holmberg &amp; Persson, 1980)</th>
<th>Damage size (m) predicted by damping law (Hustrulid et al., 1992)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>Kimulux, Ø 22 mm</td>
<td>0.15 – 0.35</td>
<td>0.45 – 0.60</td>
<td>0.60 - 70</td>
</tr>
<tr>
<td>64</td>
<td>Kimulux, Ø 22 mm</td>
<td>0.15 – 0.40</td>
<td>0.45 – 0.60</td>
<td>0.45 – 0.50</td>
</tr>
<tr>
<td>64</td>
<td>Gurit, Ø 22 mm</td>
<td>0.10 – 0.20</td>
<td>0.40 – 0.55</td>
<td>0.05 – 0.10</td>
</tr>
</tbody>
</table>

Figure 20: Saw-cut surface across the half cast (a) in the magnetite ore drift showing very fine cracks, however, inspection of saw-cut blocks revealed intense tangential cracking and (b) in the waste rock drift showing visible radial cracks. (Photos adapted from Nyberg et al., 2000c)
In the waste rock radial cracks were visible both in the half cast (see Figure 20 (b)) as well as in the saw cuts. The waste rock is more brittle (compressive strength of 300 MPa) than the magnetite ore (compressive strength of 120 MPa).

5. MALMBERGET UNDERGROUND MINE DRIFT TEST

Between 1994 and 1995 SveBeFo conducted blast damage investigation at the Malmberget underground mine in cooperation with LKAB. Details of this work can be found in Fjellborg & Olsson (1996). The objective of this study was to investigate the possibility to increase the advance while at the same time minimize blast-induced damage by using pre-drilled large diameter cut hole. The cut hole was 250 or 300 mm in diameter, which is about 4 to 5 times the nominal diameter of a standard drift blast hole which is 64 mm (see Figure 21). The length of the large cut hole was about 32 m and the blast holes were advanced in 7.5 m rounds. This enabled drifting long rounds to increase the advance. Overall this test included a total of 60 long drift rounds at a depth of 790 m.

After each blast round visual inspection was performed on the rock and the half casts were assessed. Slots were cut across the half cast into the drift wall for further examination. The exposure of half casts or half pipes was important in the examination of the blast induced cracks. Cracks emanating from the half casts are considered as blast-induced cracks, while cracks not emanating from half casts were considered as either stress-induced or natural cracks depending on the characteristics, as illustrated in Figure 22.

Borehole camera logging was also conducted to complement examination of half casts and saw cuts.
Figure 21: Test drift with large 250 or 300 mm cut hole and 64 mm blast holes (adapted from Fjellborg and Olsson, 1996).

Figure 22: Blast-induced cracks originate from half-pipes, while natural and stress-induced cracks do not (modified after Olsson et al., 2004).
5.1 Summary of test results

Results from borehole camera logging of the blast-induced damage are shown in Table 3, while those observed on saw cuts are shown in Table 4. Camera borehole logging revealed crack lengths of 0.8 – 1.2 m, while saw cut examination revealed 0.35 – 0.5 m. It may be possible that the borehole camera could capture stress-induced fractures that may not be easily differentiated from the blast-induced cracks.

Half casts are important indicators of the quality of perimeter blasting (see Figure 23). For the Malmberget tests the appearance of the half casts varied greatly with the type of explosive, the initiation system and different combinations of the two. Best results, 60% of the half casts, were obtained with electronic caps and 80 g/m detonating cord as smooth blasting explosives for the contour holes (see Figure 24). Strings of emulsion in the contour holes were also observed to produce good results. Standard caps with 3500 ms in the contour reduced the number of half casts, which was believed to be attributed to scatter in the initiation of the standard caps. Ordinary rounds produced only 30% of the half casts.

Examination of the saw cuts showed that holes charged with electronic caps together with smooth blasting produced no visible cracks. Holes with standard rounds showed significant amount of long radial cracks (see Figures 25 and 26).

<table>
<thead>
<tr>
<th>Borehole #</th>
<th>Charge</th>
<th>Borehole length (m)</th>
<th>Mapping depth (m)</th>
<th>Damage thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Emulsion</td>
<td>25</td>
<td>24</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>String + EPD</td>
<td>42</td>
<td>25</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 4: Result from camera logging (adapted from Fjellborg & Olsson, 1996)

<table>
<thead>
<tr>
<th>Charge</th>
<th>Maximum crack length – dominantly radial cracks.</th>
</tr>
</thead>
<tbody>
<tr>
<td>String + EPD</td>
<td>0.5</td>
</tr>
<tr>
<td>Emulsion</td>
<td>&gt;0.35</td>
</tr>
</tbody>
</table>

Table 5: Result from damage mapping on saw cuts (adapted from Fjellborg & Olsson, 1996)
Figure 23: The excavated drift showing the half casts or half pipes (photo adapted from Fjellborg and Olsson, 1996).

Figure 24: Observed half casts with different charges with 250 and 300 mm large cut hole (adapted from Fjellborg & Olsson, 1996).
Figure 25: Radial cracks from holes completely filled with emulsion (photo adapted from Fjellborg & Olsson, 1996)

Figure 26: Long radial cracks developed from using string emulsion + EPD (photo adapted from Fjellborg & Olsson, 1996).
6. BLAST DAMAGE INVESTIGATION AT ÄSPÖ’S TASQ TUNNEL

In 2003 a tunnel was developed at the Äspö Hard Rock Research Laboratory (AHRL) for a pillar stability experiment, eventually known as APSE (Äspö Pillar Stability Experiment) or TASQ in SKB tunnel database. A blast-induced damage investigation was conducted during the excavation of the tunnel. The details of which can be found in Olsson et al (2004). There was a high requirement to minimize damage in the pillar during the tunnel excavation by drill and blast method. A primary objective was to test if the current state-of-the-art in smooth blasting would be able to produce less pronounced damage to the remaining rock. Since the tunnel was originally intended for rock mechanics studies it was intentionally oriented perpendicular to the direction of the maximum in-situ stress in order to also the study the effect of maximum stress loading on the tunnel during the excavation. This also provided the opportunity to study the effect of high in-situ stresses on the development of blast-induced cracks. The experiment was conducted at a depth of 420 m in high stress environment.

The tunnel was excavated in two phases (see Figure 27), the first 30 m was a normal horse-shoe excavation and the second 40 m was an excavation with both rounded roof and floor. The second phase, where most of the blast damage investigation was conducted, was excavated in two stages; top heading and floor benching (see Figure 28). The top heading consisted of Ø 102 mm cut-holes and Ø 48 mm blast holes (see Figure 28 (a)).

The dominating rock types at the test site were mainly plutonic diorite and granite. The density of the rocks was 2700 kg/m³, and the compressive and tensile strengths of approximately 200 MPa and 14 MPa respectively.
Figure 27: ASPE tunnel profile (adapted from Olsson et al, 2004)

Figure 28: Excavation was conducted in two stages: (a) top heading and (b) floor benching (adapted from Olsson et al, 2004)
6.1 Summary of test procedures

The excavation was performed in 1.5 to 4.5 m rounds to study the blast damage. Only cartridged or packaged explosives were used in order to have control over blast-induced damage within the prescribed limit. The blast holes were 48 mm in diameter, whilst the cut holes were 102 mm in diameter. The column charge diameter ranged between 22 and 25 mm. A spacing of 0.45 m and burden of 0.5 m were used for the contour holes, creating a tighter pattern than usual. For the stoping holes a 0.6 x 0.6 m drilling pattern was used. For the perimeter and helper holes a small diameter pipe charge consisting of Dynotex explosive brand was used. Both the NONEL and electronic detonators were used.

After each blast rounds damage investigation was conducted by visual inspection, saw cut examination and bore hole filming. The examination was conducted on both the wall and floor. Both blast-induced and stress-induced damage were mapped.

Slots were cut both vertically and horizontally in the tunnel wall (see Figures 29) to investigate crack generation. Slots were also cut in the floor to observe damage in this part of the excavation.

For identification and measurement of blast-induced cracks there has to be at least one visible half-pipe, as illustrated earlier by Figure 22. Those originating from the half-pipe are identified as blast-induced, whilst those not originating from half-pipe are either stress-induced or natural cracks.
Figure 29: Vertical and horizontal saw-cuts through the tunnel wall (a) schematic of saw-cut method; vertically across the half-pipes and horizontally along the half-pipes, (b) example of vertical saw-cut and (c) example of horizontal saw-cut. Photos adapted from Olsson et al, 2004.

6.2 Summary of test results

After the completion the tunnel cross-sections were surveyed and the overbreaks were mapped across some cross-sections which are shown in Figure 30. The maximum overbreak was estimated to be about 0.3 m. Cores were also drilled after the completion of the tunnel for instrumentation purposes. Sonic measurements were performed on these cores and the depth of damaged zone estimated to be about 0.3 m (Staub et al., 2004)

The longest cracks in the wall were about 0.4 m while in the floor it was about 0.12 m. The number of blast-induced and stress-induced cracks and their average lengths are shown in Figures 31 and 32 respectively.

It was also observed that simultaneous initiation gave shorter cracks, while decoupling reduced the number as well the extent of the cracks. However, when water was filled in the blast holes the positive effects of decoupling was reduced or even eliminated altogether.
In the floor most of the cracks were in the horizontal direction and were not emanating from the half-casts. These were concluded to be mainly stress-induced fractures.

Figure 30: Mapped overbreak of some cross-sections (after Olsson et al, 2004).

Figure 31: Blast-induced cracks (after Olsson et al, 2004)
Figure 32.  Stress-induced cracks (after Olsson et al, 2004)

7. KEY RESULTS FROM SVEBEFO STUDIES

The SveBeFo investigations identified the following parameters to influence the development and extent of blast-induced.

- Explosive properties
  - Explosive type
  - Explosive density
  - Detonation velocity
  - Initiation method
- Geometrical parameters
  - Borehole diameter
  - Coupling ratio
  - Burden
- Rock mass parameters
  - Rock mechanical properties
  - Rock mass characteristics (natural fractures, etc)
  - Orientation of natural fractures with respect to shockwave path.
Under carefully controlled contour blasting conditions the average length of the blast induced cracks is approximately 0.3 m, while it averages about 0.5 m in large rounds as in LKAB’s Kiruna and Malmberget mines. The best results (less cracks in quantity and extent) were obtained with decoupling of blast holes and instantaneous firing. Worst results (more cracks in quantity and extent) were observed when using high VOD explosives and addition of water into decoupled blast holes.

8. END REMARKS

The SveBeFo investigation of blast damage was largely based on visual inspection and fracture or damage mapping of saw cut surfaces. Vibration analysis, overbreak profiling and borehole filming were also performed at tunnelling sites. Several systematic multiple-hole blasting were performed under controlled conditions. In this way it was possible to relate the damage due to blasting to the various parameters investigated. A method was devised for systematic investigation of the blast-induced damage with a follow up or verification of this method.

One of the main advantages of the SveBeFo approach, by saw cuts and visual inspection, is that, it is easier to identify and differentiate blast-induced damage from stress-induced damage. This is possible though with the indirect methods, such as the geophysical methods. On the hand geophysical methods have advantage to scan larger volumes and detect changes the inherent properties of the damaged rock.

The SveBeFo studies were oriented towards the development of better or improved technique for minimizing blast-induced damage for tunnelling and drifting, in hard rocks, where perimeter blasting is of significant importance. Furthermore, the Kiruna tests were particularly important in that, the advance rate of drifting can be improved while at the same time keeping the blast-induced damage as minimum as possible.

Under controlled conditions it was observed that average thickness of the crack lengths was about 0.3 m. In worst cases some cracks extended as far as 1.2 m. The best results (less cracks in quantity and extent) were obtained with decoupling of blast holes and instantaneous firing. Worst results (more cracks in quantity and extent) were observed when using high VOD explosives and addition of water into decoupled blast holes. Other important factors such as; blast hole size, burden and
spacing, pre-existing cracks, in-situ stress, and strength and stiffness of the rock, also
affected the extent, quantity, and spatial distribution and orientation of the cracks.
Some of the notable from conclusions from the SveBeFo studies can be summarized
as follows:

- Crack lengths decrease with a decreasing couple.
- Fully charged holes show a more complex crack pattern with interacting
  cracks.
- A high velocity of detonation results in many short cracks around the bore-
  hole.
- For some explosives the crack lengths increase with an increasing charge
  concentration.
- Arc-shaped subsurface cracks may occur when the spacing increased.
- The time delay between initiation of the different holes is important;
  - an instantaneous initiation of the different holes is important,
  - the crack lengths increase with increasing delay time,
  - even delay times as low as 1-ms give crack lengths more like a single hole
    blasts,
  - sequential micro-interval (zipper) blasting is inferior to instantaneous
    initiation,
  - traditional smooth blasting procedures give unnecessarily long cracks and
  - alternating initiation sequences may give short cracks.
REFERENCES


