Perimeter blasting in granite with holes with axial notches and radial bottom slots

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ABSTRACT: Five single perimeter rows, each with 8–13, 2–3 m deep $\varnothing$ 64 mm holes have been blasted in a granite quarry to develop a technique for perimeter blasting with slotted holes that decreases the blast damage primarily in road cuts and consequently the maintenance costs. Most holes had radial bottom slots, which were cut with high-pressure abrasive water jets. The rounds were surveyed and filmed, the bench faces and rock walls were mapped and the cracking behind the half-casts was detected. The results give a description of the breakage and the cracks in the remaining rock.

The technique developed uses no subdrilling and a burden $\times$ spacing of 1.0×0.8 m. The bottom slots are about 75 mm deep and decoupled $\varnothing$ 22 mm column charges with a 50 g primer are used instead of a bottom charge. Electronic Programmable Delay (EPD) caps are used to achieve a simultaneous firing of the blast-holes.

The breakage was fine and the excavation surfaces were very flat with undamaged half-casts and shallow radial cracks behind. A continuous fracture is formed along the toe line, which helps with the build-up of an undamaged nose below the holes. The continuous fracture also shields the nose from cracks that start from the column parts of the blast-holes above. A firing scatter of ± 6 ms is enough to seriously offset many of the advantages of the technique and axial notches can not replace simultaneous initiation.

The technique is technically very promising. Limitations and requirements associated with it are discussed. New, production oriented trials have subsequently been made.

KEYWORDS: Perimeter blasting, notches, slots, no bottom charge, no subdrilling, electronic detonators, blast damage, crack detection, fracture mapping, granite.

1 INTRODUCTION

The basic ideas of using notched or slotted holes in rock blasting are two;

1. to guide the direction of crack growth and
2. to lower the pressure and hence the amount of explosive necessary to drive the cracks.

Their use has a potential in cautious blasting (presplitting and smooth blasting e.g.) of slopes, tunnel walls, etc. by improving the smoothness of the final surface and by decreasing the blast damage in the remaining rock. See Figure 1.

The upper part of Figure 1 shows the standard way of perimeter blasting recommended in Sweden, with its positioning of a bottom charge at the toe (Hållerstrand 1991). The lower part of the figure shows the vision of using simultaneous firing of notched and slotted holes to remove the subdrilling and the bottom charge and to

Road cut excavation, 5:1 slope

- smooth blasting with firing scatter

Figure 1. Potential improvements of using holes with axial notches and bottom slots.

obtain a slope with considerably less blast damage.

'Axial notching' of blast-holes has a long history in ornamental stone quarries (Tsoutrelis et al. 1997). SveBeFo/SveDeFo have used axial notching of blast-holes in blasting projects too. In the Hakunge quarry, e.g. (Bjarnholt et al. 1988, Holloway et al. 1987), the holes could be drilled at a 40% larger spacing and charged with only 50% of the explosive and yet give a surface with an equivalent roughness. In the Sofia project (Niklasson & Keisu 1992) axial notches were used in the contour holes of 9 drift rounds with $\varnothing$ 64 mm holes. High-pressure water jets with iron ore fines as the abrasive were used to cut the notches. Keeping hole spacing and charging the same as in conventional practice, the half-cast factor increased from about 30 to 40 per cent and the over break decreased from about 15 to 11 per cent. Notch depths in the range 10–20 mm were used to achieve these results.

Using electronic programmable delay (EPD) detonators to simultaneously initiate charges in unnotched contour holes had the same effect (Niklasson & Keisu 1992), but a later effort to combine the positive effects of notching with EPD detonators was

not particularly successful (Niklasson et al. 1992). Based on model tests (Bjarnholt 1986), 'radial bottom slots' were also tried in the Sofia project in order to increase the advance by 'cutting off the toes'. No beneficial effects were detected (Niklasson & Keisu 1992). Since no slots were found after blasting, this result was considered inconclusive however.

In Japan an abrasive water jet cutting system had also been developed and smooth blasting tests with holes with axial notches and radial bottom slots carried out (Nakagawa et al. 1986, Iihoshi et al. 1987). Basically they too found the axial notches to work as expected. Regarding the bottom slots they achieved a smooth toe only with low VOD explosives. They found that using crater blasting of multiple holes with radial bottom slots to create a flat foundation (smooth-base blasting) was only partially successful in the fractured limestone since the natural fractures dominated, even when deflagrating charges were used. They drew the conclusion that successful smooth-base blasting in fractured rock requires the slots to be pressurised separately, i.e. before the blast-hole columns.

Even if the Japanese experience was relatively negative, well functioning bottom slots have a much larger damage reducing potential than axial notches because their toe cutting effect might be used to do away with the concentrated bottom charge. The latter not only damages the rock heavily near the toe. It also influences the pressure time history adversely in the column part (Bjarnholt et al. 1988).

The damage suppressing effect of a simultaneous firing of contour holes with EPD caps have been shown by SveBeFo's tests in the Vånga quarry (Olsson & Bergqvist 1996). The measured effects of decoupling, explosive etc. on the length of the radial cracks behind the half casts have also been transformed into a prediction formula (Ouchterlony 1997). With this experience SveBeFo entered into the EU Brite-Euram project 'Downhole Abrasive Jet Cutting Operations in Quarrying, Mining and Civil Engineering' with Conjet AB, a manufacturer of water jet cutting equipment as associated contractor. The Swedish National Road Administration (SNRA) is a supporting partner for the Swedish part of the project. This paper describes our joint introductory verification experiments with axial notches and radial bottom slots that were carried out in 1996–1997.

2 BLASTING TESTS

Base line tests with holes with radial bottom slots were first carried out in ten cubic meter sized blocks of granite. In the middle of each a $\varnothing$ 45 mm hole was drilled to a depth of about 60 cm. In 8 of the blocks radial bottom slots were cut with essentially the same equipment that had been used in the Sofia project, Conjet Aquabrasive 330. A slurry of sub 1.5 mm quartz sand and water was pumped through a 2.2 mm nozzle, situated at the end of steel piping or lance at the bottom of the hole. The nozzle rotated with about 7.5 revolutions per minute, cutting a radial slot around the bottom. The flow was 8–10 ℓ /min of sand in 5 times as much water. At 300 bar it took 5 minutes to cut a 40 mm deep slot. The total slot diameter in a block lay either in the range 120–140 mm or within 220–230 mm, depending on cutting time. The charge arrangement consisted of $\varnothing$ 25 mm dynamite, 20–50 g, initiated by a no. 8 electric detonator under sand stemming.

Figure 2. Block no. 6 with a radial bottom slot after a shot with 30 g of dynamite.

Figure 2 shows the successful shot in block no. 6. The crack emanating from the bottom slot has cut off the bottom part of the block and protected or shielded it from the vertical cracks that emanate from the blast hole column in the top part of the block. This effect was repeated in the other blocks and relieved some of our apprehension with regards to the Japanese experience (Iihoshi et al. 1997) and it was decided to go directly to full scale tests in a quarry with good granite.

2.1 Description of Svenneby Quarry Blasting Tests

The tests were made during 1997 in the Svenneby ornamental stone quarry, owned by Göinge Blocksten AB and situated east of Norrköping on the Swedish East Coast. Three 3–4 m high benches were put at our disposal, one with virtually fracture free granite and the other two set through by fractures and pegmatite veins.

The notch and slot cutting was made with the same equipment that was used in the block tests, but with a longer nozzle lance in order to reach the bottom of the 2–3 m deep holes. The depths of the bottom slots varied, see below. It typically took about 10 minutes to cut 80–90 mm deep slots. The axial notches used were cut with a linear cutting speed of about 0.5 m per minute, giving 15–25 mm deep notches.

Drilling and charging was based on an extension of the SNRA prescribed range of $\varnothing$ 25–51 mm holes for the smooth blasting of road cuts (Hållerstrand 1991). Thus $\varnothing$ 64 mm blast-holes with 1.0 m burden and 0.8 m spacing were used as a basic pattern, with $\varnothing$ 22 mm Gurit in plastic pipe cartridges in the column. Gurit is a granular, low VOD (2000 m/s), AN based and EGDN (ethylene glycol dinitrate)

Table 1. Lay out of blasting tests in the Svenneby quarry.

Round no.	Hole no.	Bottom slots mm	Axial notches mm	Hole spacing m	Initiation scatter ms	Toe state	Bottom primer
1:1	2-5	90	-	0.8	± 0	free	at bottom
fracture free	6-9	-	-	0.8	± 0	free	at bottom
2:1	1-4	-	-	0.8	± 0	free	at bottom
fractured	5-8	90	15-25	0.8	± 0	free	at bottom
rock	9-11	50	-	0.8	± 0	free	at bottom
	12-13	110	-	0.8	± 0	free	at bottom
1:2	1-5	75	15-25	0.8	± 6	confined	at bottom
fracture free	6-8	75	-	0.8	± 6	confined	at bottom
3:1	1-5	75	-	1.2	± 0	free	at bottom
fractured	5-9	75	-	0.8	± 0	free	at bottom
3:2	11-13	75	-	0.8	± 0	confined	3 cm up
fractured	13-16	75	-	0.8	± 0	confined	at bottom
rock	16-19	75	-	1.2	± 0	confined	at bottom

sensitised explosive. Five rounds were blasted, each consisting of a single row of 8-13 holes and altogether 48 holes.

The quarry benches were separated by sub-horizontal bottom joints. Thus the bottom of each round was not confined as in ordinary blasting but relatively free. To account for this, the holes were not drilled down to the joints but to a sub-horizontal toe line marked out on the bench faces about 1 m above the bottom joint. No regular bottom charge was used, only a $\varnothing 17 \times 150$ mm Nobelprime, 50 g primer to ensure good initiation. The linear charge concentration of the primer is 0.35 kg/m which is lower than the 0.40 kg/m of the $\varnothing 22$ mm Gurit. Its VOD of 6500 m/s is higher however. The holes were unstemmed. EPD caps manufactured by Rinobel AB, a subsidiary of Dyno Nobel, were used in the firing of the blast-holes.

The lay out of the tests is shown in Table 1. In the spring, rounds 1:1 and 2:1 were blasted in order to expand further the block test results under perimeter blasting conditions. Various combinations of bottom slots and axial notches were used, including holes without either. Bottom slots of different depths were used in order to see whether this parameter affected the results.

The stress concentration at the root of an axial notch is higher than that at the root of a radial bottom slot of the same depth. It was thus suspected that the crack growth from the notches might have an adverse effect on the crack growth from the radial bottom slots. The notches were thus made considerably shallower than the slots.

The holes were fired simultaneously in rounds 1:1 and 2:1. The following measuring and monitoring was made:

- hole depth, uncharged hole length, spacing and burden before blasting,
- manual fracture mapping of the face before and after blasting,
- video and high-speed filming of the rounds (made by Dyno Nobel AB),
- surface scan lines to obtain roughness before and after blasting (made by the SNRA), and

Table 2. Drilling, blasting and excavation surface data for the Svenneby rounds.

Round no.	Hole depth m	Toe spacing m	Burden m	Slot depth mm	Notch depth mm	Un-charged m	Angular dev. cm/m	Slot position cm	Half-cast ratio %	Nose depth cm
1:1	2.4	0.80±0.02	1.03±0.03	85-93	-	0.4	2.3±2.2	3±5	100±0	45-55
2:1	2.5	0.80±0.04	1.06±0.09	45-113	14-25	0.4	2.9±1.1	-3±5	94±12	35-60
1:2	2.3	0.80±0.03	1.0	65-77	14-27	0.1	0.9±0.7	9±4	66±30	0-35
3:1	2.1	0.80±0.04	1.2	63-83	-	0.2	0.9±0.8	4±9	42±30	2-75
3:2	2.6	0.80±0.02	0.95±0.06	61-85	-	0.4	0.7±0.6	-9±7	76±17	25-52

- half-cast ratio and crack lengths behind half-casts by dye penetrant studies of cut sections.

The spring rounds were successful and this governed the lay out of rounds 1:2, 3:1 and 3:2, which were blasted in the fall. The focus was on repeating the spring results. The effects of firing scatter, shallower bottom slots, a larger hole spacing (1.2 m instead of 0.8 m), added confinement and a spacer between the primer and the hole bottom to suppress the blast damage underneath the hole bottom (Haas 1964) were investigated at the same time.

In addition we unwittingly came to observe the effects of presence of water in the annulus between charge and blast hole wall and of non-perfect drilling and notching/slotting such as holes not drilled to the planned toe level, a bottom slot positioned too high in the hole and a misaligned axial notch.

The measurement and monitoring of the fall rounds was not as extensive as for the spring rounds. Data about the drilling, notching/slotting and quality of the remaining rock face have been collected in Table 2, given either as an average, average $\pm$ standard deviation or a range.

2.2 Description of rounds

Round no. 1:1

The blast fume plumes in the high-speed film show that the holes fired virtually simultaneously as planned, see Figure 3. The mapping of the bench face depicts its preblast status with visible fractures (continuous lines), half casts (vertical dashed lines), blast-hole toe line (horizontal dashed line), a pegmatite vein (vertical thin zone) and ridges (undulating lines).

The rock moved out like two monoliths, separated by the main horizontal fracture. The top half moved faster and the bottom half rotated faster. The throw was 30-35 m and the muck pile consisted of many boulders and relatively few small pieces.

The remaining rock surface was extremely smooth and all half casts were intact, Figure 4. The white stripes between the blast holes are the regions where the cracks that emanate from neighbouring blast holes have met. This is also evidence of a simultaneous firing.

Beneath holes no. 2-5 a 'nose' of virtually intact rock is visible. The nose starts at a nearly continuous 'toe line fracture' which is formed by cracks that have emanated from the bottom slots. The nose protrudes from the face as a quarter circle and is about 0.5 m deep at the bottom joint where it is fully developed beneath holes no.

Figure 3. Bench face of round 1:1 directly after initiation, with preblast mapping.

Figure 4. Photo of postblast excavation surface behind (wall after) round 1:1, hole numbering from right to left.

2–4. Beneath the unslotted holes no. 6–9 however, the rock face continues almost straight down to the bottom joint, see Figure 4, and a continuous toe line fracture is also missing.

Round no. 2:1

This round was blasted in more fractured rock. The face was weathered with two main sub-horizontal fractures and several pegmatite veins. Again the holes fired virtually simultaneously. Apart from the fragmentation becoming finer, round 2:1 broke out like round 1:1. Figures 5–6 show the postblast fracture mapping of the excavation surface (wall), including the remaining half casts. The radial slots at the bottoms of holes are shown as are the cracks emanating from them. The tips of these

Figure 5. Fracture mapping of part of wall after round 2:1, holes no. 1-7, with toe line fracture. Nose depth values given in cm.

Figure 6. Fracture mapping of part of wall after round 2:1, holes no. 7-13.

cracks are shown as filled circles. Such cracks from neighbouring holes sometimes intercept, sometimes overlap and intercept and sometimes they stop at an existing fracture. Like in round 1:1 they form a nearly continuous toe line fracture underneath the slotted holes, no. 5–13, an exception being hole no. 6.

Underneath the slotted holes a 0.5 m wide nose was again seen. A section is shown in Figure 7 and numbers are given in Figures 5–6. Underneath the unslotted holes, no. 1–4, the nose is virtually absent like underneath the unslotted holes in round 1:1.

As Figures 5–6 and the numbers therein show, there is only a small difference between nose depth underneath holes no. 5–8, which have axial notches, and underneath holes no. 9–13, which have none. Excepting hole no. 6, the same is true for the toe line fracture. This shows that our suspicion that the axial notches would have an adverse effect on the cracking from the radial bottom slots was unfounded, at least for notches that are 15–25 mm deep.

The bottom of hole no. 6 lies 7–8 cm above its neighbours and in addition the slot was unintentionally cut 6 cm above the bottom. The vertical cracking has continued a bit below the bottom slot, but the 'nose building effect' of holes no. 5 and 7 have suppressed the vertical cracking in the face plane.

A close up of hole no. 6, Figure 8, shows two other phenomena. Firstly, the right-hand axial notch was unintentionally directed into the back. Consequently it steered the crack in that direction and it has caused a long section of rock to be removed, i.e. caused over-break. Secondly, the left-hand axial notch, which was correctly directed along the intended excavation surface, happened to end at an intersecting vertical fracture. The latter has completely overridden the crack steering effect of the notch and also caused over-break.

Figure 7. Nose below toe line underneath holes no. 5–9 of round 2:1.

Figure 8. Detail of hole no. 6 from round 2:1, with misplaced bottom slot and misaligned right hand axial notch.

The remaining rock face is again extremely smooth but the bench face after the blasting of round 2:1 has more steps and other small-scale changes in the surface, typically over distances of 5–10 cm. The ratio of intact half casts is 94 per cent. The 6 per cent losses are mainly due to partially cracked half casts in holes no. 1–3 and a missing top part of hole no. 13.

Round no. 1:2

Round no. 1:2 was blasted directly behind round 1:1. The nose remaining from round 1:1 added confinement to the toe and the effect of increased initiation scatter, such as in pyrotechnic delay caps, was investigated. All holes had radial bottom slots. Holes no. 1–5 also had axial notches but not holes no. 6–8. See Table 1.

The pyrotechnic delay firing was simulated with EPD caps. The simulation was based on the first sequence of pseudo random numbers, which transformed into a normal distribution with a scatter ± 6 ms, that met the requirement of the corner holes not firing first. See Table 3. The firing times were rounded to the nearest whole ms.

Seen from the face it turned out to be:

Table 3. The relative firing times of the holes in round no. 1:2.

Time	+8	+2	+10	+13	+16	+2	±0	+6 ms
Hole no.	8	7	6	5	4	3	2	1

— face

The blasting process could be followed well on the high-speed film. Muzzle flashes and fumes appear in the right time frames. An analysis gives estimates of the crack velocity in granite as 250–400 m/s and the velocity with which the gases penetrate into the cracks as roughly 300 m/s. Some fumes penetrate to the free face through existing fractures. None were however seen ejecting from sections of the fractures where water had been percolating before the shot. All the blast holes had been rinsed with compressed air and, as far as could be judged, they were dry during the charging.

The cracking seen in the high-speed film is much more intense in front of the unnotched holes no. 6–8 than in front of the notched holes no. 2–5. The rock mass split around a vertical crack or fracture between holes no. 5–6, forming a plough rather than a straight front as in rounds 1:1 and 2:1.

Superficially seen, the result of round 1:2 appeared to be the same as from round 1:1, i.e. good breakage. A closer inspection showed however that the remaining face is substantially more cracked and the surface much rougher. Many of the half casts are damaged and the nose below the toe line is not as developed, see Figures 9–10. These figures show a postblast photo of the excavation surface after round 1:2 and the corresponding fracture mapping respectively, which enhances some of the features seen on the surface.

Figure 9. Photo of postblast excavation surface behind (wall after) round 1:2.

Figure 10. Fracture mapping of wall after round 1:2, holes no. 1–8, with virtually absent toe line fracture and roughness description. Nose depth values given in cm.

All half-casts except those of holes no. 2 and 7 are damaged. The whole lengths of the casts of holes no. 1 and 3–5 below the horizontal fracture are cracked. The ratio of intact half casts is only 66 per cent as compared with 100 per cent for round 1:1. Furthermore many of the bottom slots seem to have had no effect. Nor is there any continuous toe line fracture between holes no. 3–6.

A conclusion of this is that the surface smoothness, the ratio of intact half casts, the length of the toe line fracture and the nose development all deteriorated when a non-simultaneous firing of the blast-holes was used in round 1:2. Nor was any positive effect of the axial notches seen.

Round no. 3:1

This round was blasted in a new bench with fractured granite. To avoid too much interference from a pair of sub-vertical joints that were sub-parallel to the bench face, a burden of 1.25 m was chosen. The spacing between holes no. 1–5 was 1.2 m and the spacing between holes no. 5–9 was 0.8 m. All holes were fired simultaneously with EPD caps. See Table 1.

The high-speed film showed that the breakage process was essentially identical to that in rounds 1:1 and 2:1. Geological features dominate the postblast excavation surface. The two sub-vertical joints have caused the crest to be blown off between holes no. 8–9 and holes no. 4–7. Figures 11–12 show the postblast excavation surface of round 3:1.

Many of the cracks in the half casts can be explained by the presence of these joints. This reduces the ratio of intact half casts to only 42 per cent. The excavation surface of round 3:1 is smooth however and has a structure that differs little from

Figure 11. Photo of postblast excavation surface behind (wall after) round 3:1, with nose below toe line.

Figure 12. Fracture mapping of wall after round 3:1. Nose depth values in cm.

that of the face before blasting. There was no directly observable difference in the surface that could be attributed to the use of different hole spacing values, 0.8 or 1.2 m. As for the cracking see section 2.3 below.

A continuous toe line fracture runs from hole no. 9 to hole no. 4. There the continuity is broken by a surfacing joint which has prevented the fracture from growing towards hole no. 3. The nose below the toe line is well developed except where this joint cuts in, Figure 12. The average nose depth along the bench is about 0.5 m.

Round no. 3:2

Round 3:2 was placed directly behind round 3:1 whose remaining nose added to the confinement of the toe. The burden was 1.0 m and the spacing 0.8 m between holes no. 11–16 and 1.2 m between holes no. 16–19. Underneath the primer in holes no. 11–13, a 32 mm high hollow plastic spacer was placed in order to suppress the formation of conical cracks in the hole bottoms. All the holes were fired simultaneously with EPD caps. See Table 1.

In round 3:2 water was present in some blast-holes. Holes no. 16 and 17 could not be emptied by blowing with compressed air and were only charged with 1/2 cartridge of Gurit on top of the primer instead of the usual 2 cartridges. Water was also present in hole no. 15. Round 3:2 was monitored by video. In the first real frame with muzzle flashes, the ejection front is not as even as in round 3:1. Real flashes are seen only from holes no. 12–14 and 17–19.

From holes no. 11 and 15 there seems to flow blast fumes and from holes no. 16–17 water. The water plumes rise with a velocity of 150–200 m/s but the gas plumes only half as fast. Even so the breakage process looks essentially like what has been previously described for all rounds except round 1:2.

The postblast excavation surface was dry except around holes no. 15–17. Here the rock surface was rougher, sometimes with hackle like patterns, and more cracked, see Figure 13. There were even crushed and broken regions in the half casts and in the bottom slots. The ratio of intact half casts is 62 per cent, or if the water containing parts in holes no. 15–17 are discounted, 76 per cent. This is much higher than the 42 per cent from round 3:1. It is even higher than the 66 per cent from round 1:2 where the rock was considerably less fractured to begin with.

A relatively continuous fracture runs along the whole toe line. The continuity is broken at three places but this doesn't stop the development of a nose along the whole bench. The nose may not be as even as in round 3:1 but its average depth is 0.4 m. That the nose was relatively undamaged is proven by that a 5 m long intact

Figure 13. Fracture mapping of wall after round 3:2, with roughness description. Nose depth values in cm.

Figure 14. Photo of block consisting of intact nose region below holes no. 11–16 of round 3:2. Photo taken after postsplit made to obtain blocks for crack detection.

piece from below holes no. 11–16 could later be extracted for crack detection, see Figure 14.

Rounds 3:1 and 3:2 both showed good breakage. No effect of the increased confinement from the nose remaining after round 3:1 could be observed in round 3:2 results.

2.3 Crack detection results

Blocks were extracted from rounds 2:1, 1:2 and 3:2 for diamond sawing and crack detection by dye penetrant, like in the Vånga tests (Olsson & Bergqvist 1996). The block extraction was made by drilling a closely spaced line of drill holes behind the wall and blasting them lightly. Suitable blocks, with the prospective cuts marked out, were then trucked to a facility for diamond sawing. The sawn surface was then cleaned, dried and Bycotest RP 20 red penetrant applied. After washing off of surplus penetrant, the developer was applied and the cracks became visible as red streaks against a white background, see Figures 15–20.

Round 2:1

From this round five blocks were taken from the wall, i.e. the column part, two each covering holes no. 4–5 and holes no 8–9 and one covering holes no. 11–12. From these, nine cuts with half casts with cracks were obtained. See Figures 5–6 for the

Figure 15. Undisturbed radial cracks behind half-cast of notched hole no. 8 of round 2:1.

Figure 16. Radial cracks behind hole no. 5 of round 2:1, disturbed by existing fracture.

Figure 17. Conical crack or blast cone underneath the slot in hole no. 7 of round 2:1.

Figure 18. Cracks behind water filled hole no. 17 of round 3:2, spacing 1.2 m.

Figure 19. Cracks behind dry hole no. 18 of round 3:2, disturbed system, spacing 1.2 m.

Figure 20. Cracks behind notched hole no. 3 of round 1:2, firing with scatter.

locations of these cuts. The lengths of the radial cracks have been measured from the rims of the blast-holes. Data are given in Table 4.

Note that Tables 4–6 consist of two halves. The top half has block numbers like 5:3 that refer to cuts through the half casts, which show mainly radial cracks. The bottom half has block numbers like 5B that refer to cuts through the bottom slot, which show mainly cone cracks.

A 5 cm deep diffuse zone of intense cracking like in Figure 15 may be seen in many of the cuts. This is what Olsson and Bergqvist (1996) call ‘*crushing cracks*’. The number of radial cracks protruding beyond this zone lies between 1–5. The maximum crack length is 40 cm and there is no significant difference between cracks emanating from holes with axial notches and those emanating from unnotched holes. Cracks that emanate from blast-holes that have been ‘*disturbed*’ by existing fractures or pegmatite veins, see Figure 16 e.g., are however on average more than twice as long as those emanating from undisturbed holes.

Three blocks were taken from the nose below the toe line of holes no. 5, 7 and 11–12. On these the bottom slots are clearly visible. Cut 7B had a 30–35 cm deep conical crack, see Figure 17. In the other two cuts the crack depth doesn’t exceed 5 cm. Thus using bottom slots doesn’t completely suppress the formation of these cone cracks but at least the blast damage in the nose below the bottom slots is shallower than the radial cracks behind the half-casts.

Rounds 1:2 and 3:2

From round 1:2, four blocks were taken from the wall and two from below toe line of holes no. 5 and 7. See Figure 10 for the locations of these cuts. One block was a nose boulder from round 1:1. The crack data from round 1:2 are collected in Table 5.

From round 3:2, three blocks were taken from the wall. One consisted of the intact nose region below holes no. 11–16, Figure 14, but cuts were only obtained from holes no. 12–14. See Figure 13 for the locations of the horizontal cuts. The data from round 3:2 are shown in Table 6.

Cut 17:3 in Figure 18 shows a crack pattern from a water filled hole and cut 18:2 in Figure 19 shows a pattern from a dry hole. Both had a 1.2 m spacing. The latter has been disturbed by a fracture about 20 cm behind the wall. The cracks behind the half-casts of the water filled holes are much longer, c.f. Figures 18 and 19. See also Figure 15. The presence of water not only makes the blast-hole walls have a more crushed appearance but also more than doubles the zone of diffuse cracking, from about 5 to 8–20 cm. This is in accord with the blast-hole pressure evaluations of Sanchidrian et al. (1998).

In cuts 17:3 and 18:2 one can also see radial cracks that are directed within 15–25° from the face and which tend to curve back toward the face. They are called ‘*arc shaped cracks*’. Since they lie within 15–25° from the face, they don’t penetrate more than 10–15 cm into the wall.

The holes in round 1:2 were fired with scatter between the initiation times. As intended cracks have propagated from the notch roots along the excavation surface but cut 3:1, e.g. displays other features as well, Figure 20. There is firstly another notch root crack, heading 25 cm into the rock, angled 90° to the face and a slightly longer angled crack may be seen in cut 3:1. Thus, the axial notches don’t appear

Table 4. Positions of saw cuts for crack detection in round 2:1 and descriptions of resulting cracks. Note two table halves with different types of cracks.

Block no.	Position rel. subhorizontal vein / fracture	Saw cut position along hole	Cut no.	Segment angle deg.	Source of disturbance	Diffuse zone cm	Max crack length cm	No. of radial cracks	Axial notches
4:2-5:2	below upper	45 cm below vein in no. 5	4:2	60	fracture	5	10	1	none
			5:2	180	none	5-6	5	1	yes
5:3	below upper	45 cm below vein in no. 5	5:3	170	visible fracture	0	36(20)	4	yes
8:1-9:1	above upper	30 cm above vein in no. 8	8:1	180	none	5	15	5	yes
			9:1	60	non-visible fracture	0	16	2-3	none
8:2-9:2	below upper	30 cm below vein in no. 8	8:2	180	none	5	5	0-1	yes
			9:2	180	non-visible fracture	5	18	2-3	none
11:3-12:3	below upper	20 cm below vein in no. 11	11:3	180	induced fracture	5	13	1	none
			12:3	60	pegmatite vein	20	40	2-3	none

Block no.	Position	Saw cut relative face	Cut no.	Segment angle	Source of disturbance	Slot position cm	Depth of cone crack cm	Cone flanks no.	Time to cut slot min
5B	below toe line	perpendicular	5B	180	none	1.0-1.5	5	1	10
7B	below toe line	perpendicular	7B	180	none	1.5-2.0	30-35	2	10
11B-12B	below toe line	parallel	11B	180	horizontal joint	-	0	0	15
			12B	180	pegmatite vein	-	0	0	15

Table 5. Positions of saw cuts for crack detection in round 1:2 and descriptions of resulting cracks. Note two table halves with different types of cracks.

Block no.	Position rel. main fracture	Saw cut position along hole	Cut no.	Segment angle deg.	Source of disturbance	Diffuse zone cm	Notch root crack cm/deg.	Other cracks cm	No. of radial cracks
2:1	above	50 cm above	2:1	180	vein at 25 cm	0	32 / -20	15	0
3:1-4:1	above	40 cm above fracture in no. 3	3:1	180	none	2-3	25 / -90	15	2-3
			4:1	180	none	<1	- / 0	25	0
5:1-6:1	above	20 cm above fracture in no. 6	5:1	180	flaking crack	-	- / 0	-	-
			6:1	90	fracture at hole	2-3	none	3	2
7:1	above	30 cm above	7:1	170	none	2-3	none	10	2
3B	below	perpendicular	3B	180	none	1.0-1.5	5	2	15
5B	below	perpendicular	5B	180	misplaced slot	3.5-4.0	17	2	5
B	below	parallel	7B	180	none	1.5-2.0	(2)	2	5
Block no.	Position relative toe line	Saw cut relative face	Cut no.	Segment angle	Source of disturbance	Slot position cm	Depth of cone crack cm	Cone flanks no.	Time to slot cut min

to suppress cracks from growing in other directions than that in which the notches point.

Secondly, there are 3 radial cracks of about 15 cm length in cut 3:1. They are not all that well developed and lie near the surface. Even if cuts 2:1 and 4:1 display no radial cracks, see Table 5, it appears that the axial notches don't totally suppress the creation of radial cracks either.

It is conceivable that the suppression of these unwanted cracks would become more successful if the charges in the blast-holes were decreased but the decreased movement of the burden must also be considered.

Thirdly a branching crack from the bench face, a '*bench face crack*', interferes with the angled notch root crack in Figure 20. The branching crack comes from hole no. 4 on the left. Since it stops at the notch root crack we may conclude that the latter was already there when the branching crack arrived at hole no. 3. This is corroborated by the firing times, which were +2 ms for hole no. 3 and +16 ms for hole no. 4. See Table 3.

There are other bench face cracks in the cuts of round 1:2 which seem not emanate from the half-casts or their notches and presumably are a result of the firing scatter. Bench face cracks of about the same lengths also occur in round 3:2.

Basic statistics for the lengths of the different crack types are given in Table 7. The lengths of the radial cracks are measured from the blast-hole rim. From Tables 4-7 several other conclusions can be drawn. The crack lengths in Table 7 have been translated to damage depth in Table 8, i.e. the depth below the excavation surface to which the cracks have propagated in our saw cuts. Water in the blast-hole stands out as the major disturbance.

Table 6. Positions of saw cuts for crack detection in round 3:2 and descriptions of resulting cracks. Note two table halves with different types of cracks.

Block no.	Position rel. main fracture	Saw cut position along hole	Cut no.	Segment angle deg.	Source of disturbance	Diffuse zone cm	Radial cracks cm	Other cracks cm	No. of radial cracks
11:3-13:3	below	95 cm below fracture in no. 12	11:3 12:3 13:3	180 205 170	none none none	2-3 3-4 1-2	12 20 10	25 - 45 arc	2-3 3-4 2-3
14:3-16:3	below	80 cm below fracture in no. 15	14:3 15:3 16:3	150 180 180	none water water	0-1 10 20	7 36 37	- 18 -	- 4-5 >5
17:2-18:2	below	40 cm below fracture in no. 18	17:2 18:2	180 180	water fracture 20 cm behind wall	8 2-3	41 25	55 arc 52 arc	2 5
17:3-18:3	below	95 cm below fracture in no. 18	17:3 18:3	180 140	water none	10-15 2-3	40 12	60 arc 45 arc	6-7 2
11B-16B	below	parallel parallel parallel parallel parallel	11B 12B 13B 14B 15B 16B	180 180 180 180 180 180	adjoining vein none none none water water	- 2.0-2.5 1.5-2.0 1.0-1.5 - 1.5-2.0	- (2) (2) 3 - -	- 2 2 2 - -	5 5 5 5 5 5
fractured nose	broke off in sawing								
Block no.	Position relative toe line	Saw cut relative face	Cut no.	Segment angle	Source of disturbance	Slot position cm	Depth of cone crack cm	Cone flanks no.	Time to cut slot min

Table 7. Summary of statistics for crack lengths in saw cuts.

Category of cracks:	Avg. Std dev.	No.	Category of cracks:	Avg. Std dev.	No.
Radial cracks, undisturbed			disturbed by fracture or vein		
– no axial notches	12 ± 4 cm	7	– no axial notches	22 ± 11 cm	5
– notches, simultaneous	8 ± 6 cm	3	– notches, simultaneous	36 cm	1
– notches, non-simult.	15 cm	1	– notches, non-simult.	3 cm	1
Data for all undisturbed radial cracks	11 ± 5 cm	11	Data for all radial cracks disturbed by fracture or vein	21 ± 13 cm	7
Radial cracks disturbed by water in hole	39 ± 2 cm	4			
Bench face cracks	21 ± 4 cm	4	Arc-shaped cracks	51 ± 7 cm	5

Table 8. Blasting results in the Svenneby quarry, focusing on deviation from best performance.

Round no.	Half-casts %	Roughness % flat	Crack type in wall	Damage depth cm	Toe line fracture	Nose depth cm	Reason for deviation from best performance
1:1 fracture free	100	80			yes <i>no</i>	50 <u>20–25</u>	best performance <i>no bottom slots</i>
2:1 fractured rock	94	80	radial disturbed radial	10–15 <u>20–25</u>	<i>no</i> yes yes	<u>10–20</u> 50	<i>no bottom slots</i> best performance <i>nearness to joint, fracture or vein</i>
1:2 fracture free	<u>66</u>	<u>25</u>	radial bench face	10–15 <u>20–25</u>	<i>no</i> <i>no</i>	<u>20</u>	<i>firing scatter</i> <i>firing scatter</i>
3:1 fractured	<u>42</u>	50			yes yes	50	<i>joint behind wall</i>
3:2 fractured rock	76	50 <u>25</u>	radial dist. radial arc shaped	10–15 <u>40–45</u> <u>10–15</u>	yes yes yes	50	best performance <i>water in blast hole</i> <i>large spacing</i>

3 RESULTS AND CONCLUSIONS

3.1 Summary of results

Our perimeter blasting of the spring rounds 1:1 and 2:1 in the Svenneby quarry, with radial bottom slots and axial notches in the blast-holes, have shown that with simultaneously fired holes:

1. Bottom slots generate cracks that form a more or less continuous fracture along the bottom of the bench. This '*toe line fracture*' cuts off the toe and the rock above is removed with a minimal primer and without subdrilling.

2. The toe line fracture produces a '*nose*' below the toe which protrudes about 0.5 m. It also stops vertical cracks from the column part above from penetrating into the nose. It thus has a '*crack shielding effect*'.

3. This crack shielding effect was independent of a slot depth from about 50–100 mm.

4. The bottom slots don't always prevent the creation of the conical cracks that normally form beneath unslotted holes.

5. Below the unslotted holes, vertical cracks form that are a continuation of the excavation surface, i.e. the wall of the blasted bench.

6. Nearly 100 per cent of the half casts are visible after blasting and cracks inside them are only seen where the holes have not been slotted or notched.

7. Existing sub-vertical fractures often stop the growth of the cracks that emanate from the bottom slots. The observed crossing frequency was roughly 1/3.

8. The radial slots should be cut at the bottom of the blast-holes to achieve a full crack shielding effect. Yet, if there is a hole with a wrongly placed slot between two holes with correctly placed slots, the shielding effect doesn't vanish completely.

9. The bottom slots should be positioned along a straight toe line, i.e. virtually at the same level, for the slots to co-operate properly and form a continuous toe line fracture.

10. Vertical cracks start from the roots of the axial notches and follow the excavation surface if the notch is not misaligned or intersected by an existing sub-vertical fracture. In the latter cases local over or under break will occur.

11. Axial notches of up to 25 mm depth do not take away the crack shielding effect of bottom slots that are 80–90 mm deep.

12. The quality of the remaining rock, i.e. the roughness of the surface and the lengths of the cracks behind the half casts, is not really improved when axial notches are used.

13. The radial cracks behind the half casts tend to become longer when an existing fracture disturbs the blast-hole.

The principal effects of using blast-holes with radial bottom slots that are fired simultaneously are illustrated in Figure 21, which is based on Figure 11.

The results obtained from the fall rounds 1:2, 3:1 and 3:2 essentially confirm all the results stated above. All the results are summarised in Table 7. We have found that:

14. A normal initiation of the charges where there is firing scatter between blast-holes gives, in comparison with simultaneous firing;

- a rougher and more fractured excavation surface,
- a lower ratio of intact, i.e. undamaged half-casts,
- a less developed toe line fracture,
- a poorer nose build-up and
- not really longer radial cracks behind the half-casts, but
- longer cracks of other types, e.g. from the notch roots or the bench face.

15. The increased confinement from the nose left behind from a previous round probably has no negative effect on the breakage or on the other blast results.

16. The use of more shallow bottom slots, 75 mm instead of 100 mm, has decreased the cutting time to 5 minutes and given no visible degradation of the blast results.

17. The increase of hole spacing from 0.8 m to 1.2 m in parts of 2 rounds has resulted in;

- the formation of a continuous toe line crack and a nose like with 0.8 m spacing and
- probably not any longer radial cracks, but

of axial notches will not compensate for a non-simultaneous initiation and appear to add nothing but costs.

The technique is sensitive to the slot position. A slot that is cut within 1–2 cm of the hole bottom has no adverse effect on the results but one that is cut 5 cm above may have. Also, adjacent slots which differ in level by 25–30 cm definitely disrupt the continuity of the toe line fracture but slots which differ 10 cm do not. A maximum variation in slot level of ± 5 cm around the toe line should thus be on the safe side.

Further, bottom slots 45–113 mm deep have been used without any clear difference in toe line fracture formation or in nose build-up. 75 mm deep slots work well. They have been used with axial notches without losing their ability to shield the nose. Scaling our experiences to other hole diameters in hard rock we could perhaps state that when burden, spacing and charge size are scaled accordingly then the bottom slots;

- should be placed within $\varnothing/4$ mm of the blast-hole bottoms,
- should lie within $\pm \varnothing$ mm of the intended horizontal toe line and
- should be at least $\varnothing$ mm deep from the blast-hole wall.

This means that both the drilling and the slotting precision need to be high.

The cracks emanating from the bottom slots can travel at least 60–90 cm along the toe line in both directions in unfractured rock. Sub-vertical fractures or joints stopped on average 2 out of 3 of these cracks. Thus if two or more predominantly vertical fractures cut the toe line between adjacent holes, there is a major risk that the toe line fracture will be disrupted. A tentative limit to be observed before practical evidence to the contrary would thus be to use a blast-hole spacing S which is less than twice the average horizontal distance between fractures l_f , i.e. $S < 2 \cdot l_f$.

Two factors that affect the crack suppression potential of the technique adversely were found. One is water in the blast-holes, the other an increased spacing to 1.2 m instead of 0.8 m. As far as we can tell, neither impair the breakage at the toe, nor the continuity of the toe line fracture or the nose building effect though.

There are cost cutting improvements to the technique that should be tried. Will the use of detonating cord for a near simultaneous firing have the same effect as the use of the EPD caps or will the resulting side initiation diminish the crack shielding effect? Can the small primers be removed without adverse effects? Will the technique work with shallower bottom slots, say 50 mm? This would decrease the 5 minutes required to cut the 75 mm slots by about 50 per cent.

The acceptance of the method further requires that it be proven under production conditions. Will it work in less favourable rock, e.g. in fractured gneiss or in bedded sedimentary rock? Will it work as the last row in a full round where the toe is fully confined or must the row with slotted and/or notched holes be fired separately? What are the real requirements on the drilling and slotting precision?

Field trials with perimeter blasting with simultaneously fired slotted holes under production conditions have been conducted in our EU project to answer some of these questions. A 130 m long slope of 5–12 m height with 3 rows of holes, the contour plus two helper rows, has been blasted in 2 rounds. The field work and preliminary results have been reported (Ouchterlony et al. 1999) and a report on the analysed results is under way.

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