doi:10.36487/ACG_repo/2435_D-02

Experiences from confined blasting tests at the sublevel caving mine in Kiruna

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ABSTRACT

Blasting in sublevel caving is a complex process. The mechanisms in confined blasts have been studied for more than 20 years throughout a series of different experimental scales at the Kiruna mine (LKAB) in northern Sweden. Several small-scale tests as well as seven confined pillar tests, either with artificial filling material or caved masses, have been conducted to measure and observe the burden movement as well as the interaction between the blasted and the confining materials. The most recently conducted tests were on a series of production rings. A wide variation of confining materials was tested in the pillar tests, ranging from fine to boulders, to observe the behavior under different conditions as the particle size distribution of the confining material in the real case is unknown. The results from the pillar tests and the production rings showed that the burden moves with velocities varying from 10 to 32 m/s. The burden displacement varies between 0.4 and 1.6 m. The extent of the compaction zone of the confining materials can be described with an inverse exponential law. Overcompaction of the confining materials was observed in the vicinity of the burden, especially for fine filling material (< 30 mm). Additionally, agglomeration was observed on the contact surface between the burden and the confining material in the areas with high moisture content. There was evidence for apparent cohesion of the confining material which indicates the introduction of apparent tensile strength. Scaling-up the observations, the introduction of apparent tensile strength might influence the behavior of the blasted and caving materials during the flow toward the draw point.

1 INTRODUCTION

Sublevel caving (SLC) is a mass mining method implemented at the Kiruna mine owned and operated by LKAB (Luossavaara-Kiirunavaara Aktiebolag) in northern Sweden. The mining method can be vulnerable to ore losses and waste rock dilution (Bull & Page, 2000). The method utilizes a drill and blast technique. The blastholes are drilled in a fan-shaped configuration referred to as an SLC production ring. Blasting is performed under confined conditions due to material either from previous blasts and/or caved material in front of the burden (Figure 1). The confinement varies from blast to blast; it varies from open slots to fully confined and it is dependent on the characteristics of the confining material in front of the burden, i.e. particle size distribution, porosity, and compressibility. Hence, the method relies on the interaction between the blasted and caved materials. The interaction is governed by complex mechanisms. The study of the interaction mechanisms has been a subject of several studies for more than 20 years such as (Zhang, 2004), (Newman, et al., 2008), (Wimmer & Ouchterlony, 2011) and (Petropoulos, 2017). Several experimental configurations have been used to study the interaction mechanisms starting from small-scale tests, pillar tests and more recently full-scale tests considering the Kiruna mine conditions, i.e. large SLC conditions.

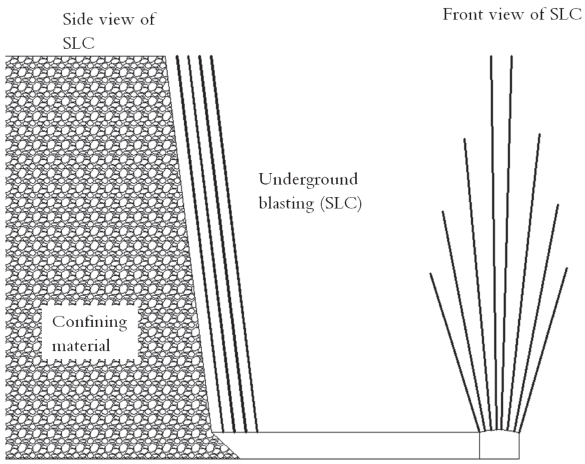

Figure 1 SLC production blasting (Petropoulos, 2017).

2 EXPERIMENTAL STUDIES

2.1 Small scale tests

Small-scale tests, based on the Kiruna mine layout at 1:75 scale, were conducted by Rustan, (2013). The findings of the study were that the short delay time (< 1 ms) between the blastholes reduced the maximum particle sizes while the maximum swell was observed at the shortest delay time (0.1 ms). The burden kinematics studied in the small-scale tests resulted in a peak velocity of approximately 24 m/s. In 2004, Zhang performed a series of small-scale tests with a scale of 1:50 SLC (10 x 10 m, sublevel x crosscut spacing). The study was to observe the effects of confined blasting on the gravity flow of the material. The results of the study showed that the blasted material swelled in two directions, i.e. toward the draw point and horizontally.

The small-scale tests were conducted by Johansson, (2011) and Petropoulos, et al., (2013). The tests had a cuboid configuration made with magnetite mortar, the results by Johansson, (2011) tests showed that the fragmentation becomes coarser under confined conditions. The confining material and the specific charge have a great influence on the fragmentation and compaction. The porosity of the matrix of the fragments in the confining material was found to be an important parameter. The burden dynamics were studied by Petropoulos, et al., (2013) in small scale experiments and the results showed that the peak velocity was around 29 m/s. Moreover, a rebound of the burden was observed as the confining material reacts to the compaction by the burden during the blast. Furthermore, a staggered pattern showed higher compaction by 15 % than that from sequential blasting due to differential movement of the burden. Based on the small-scale tests, it was concluded that the increase of the experimental scale was necessary to study the mechanisms that might be hidden. Because these mechanisms can be overshadowed by the explosive energy which cannot be scaled down to the test-scale. Based on the findings from small-scale tests, the pillar tests were designed and conducted.

2.2 Pillar tests

At the Kiruna mine, seven pillar tests have been conducted since 1996. Newman, (1996) and Newman, et al., (2008) conducted a pillar test in confined conditions to study the ore swell and to estimate the blast damage in an SLC production ring blast. The results showed that swelling varied from 2 to 17 %. This variation might be explained by the inconsistency of the degree of packing of the caved material. Wimmer & Ouchterlony, (2011) carried out a series of pillar tests to develop measurement methods for the study of burden dynamics and over-breakage. Two of the pillars were in a configuration similar to the confined conditions in the SLC method. The confining material was a mixture of ore and waste rock from drift development at the mine. The findings from those pillar tests were that the burden moved about 1.2 – 1.6 m and the compaction was in the range of 4 to 5 %.

Petropoulos, et al., (2015) and Petropoulos, et al., (2018) carried out two confined pillar tests. The conceptual design is shown in Figure 2 and it is cross-section of the experimental plan. The 1st pillar test was to evaluate the developed instrumentation and new procedures such as installation and detonation of the blastholes. The new instrumentation was composed of accelerometers and 4-point probe for displacement measurement. The instrumentation was developed to be installed in the full-scale test, which implies that certain criteria need to be met. For example, the measurement system had to be installed from the collaring of the measurement borehole toward the burden. A firm installation of the measurement systems had to be ensured to acquire reliable data, hence, an expanding grout was developed. The first pillar test was confined by coarse material, i.e. maximum particle size approximately 500 mm, considering particles size in a production scale. The confining material was from drift development of the mine. The dashed line in Figure 2 denotes the expected breakage of the burden from the pillar which acts as a piston to compress the confining material. The blasthole diameter was Ø115 mm and charged with emulsion explosive.

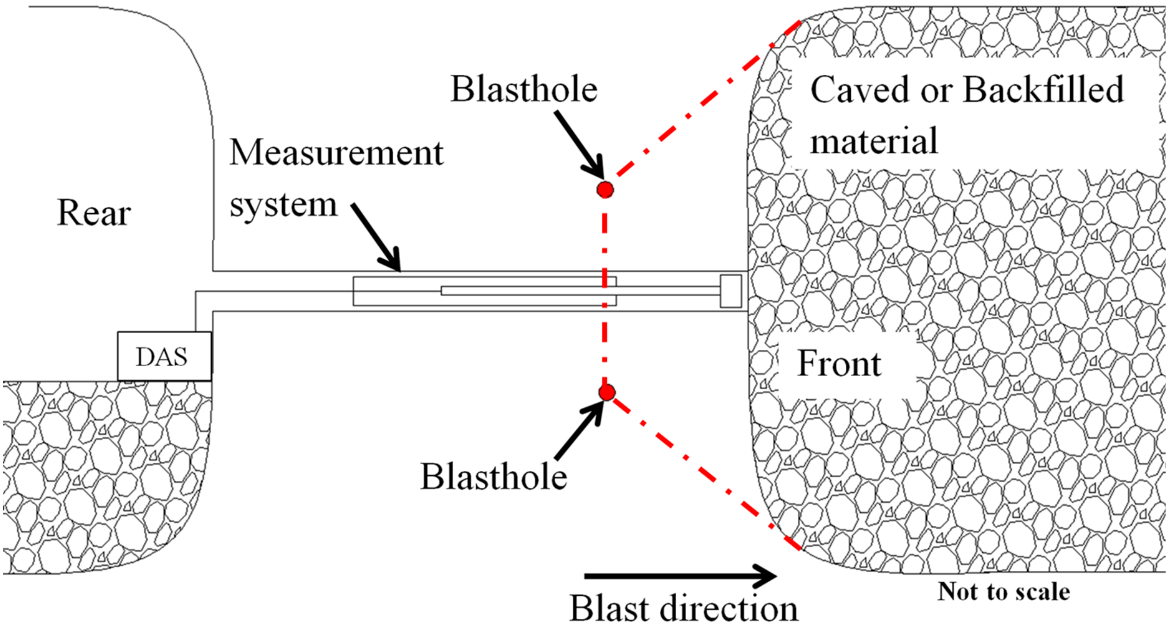

Figure 2 Experimental configuration of 1st and 2nd pillar tests (front view) (Petropoulos, et al., 2018) (DAS: Data Acquisition System).

The 2nd pillar test was confined with relatively fine material, i.e. maximum particle size approximately 32 mm. The confining material was waste material which was passed through a crusher. The confining material was studied in laboratory conditions by Petropoulos, et al., (2017) to observe the material reaction during an impact from the burden movement during blasting. This study was performed for two material conditions, i.e. dry and wet since it was expected to have the material in such conditions in the pillar tests. Moreover, different impact velocities were used to investigate the variations of the burden velocity during a blast. Figure 3 shows the experimental configuration of both pillar tests in top view, i.e. crosscut 436 was the backfilled crosscut for the 1st pillar test and crosscut 433 was for the 2nd pillar test. In both pillar tests, there was instrumentation, accelerometers, in the confining material to observe the reaction of the confining material during the blast. The 2nd pillar test was divided into two parts, i.e. the first part was the fine confining material and the second part was caved masses. Additionally, two types of measurement systems were installed, i.e. one system was based on time-domain reflectometry technology (TDR systems), the systems (M #) equipped with accelerometers and there were 2 back-up or inspection boreholes.

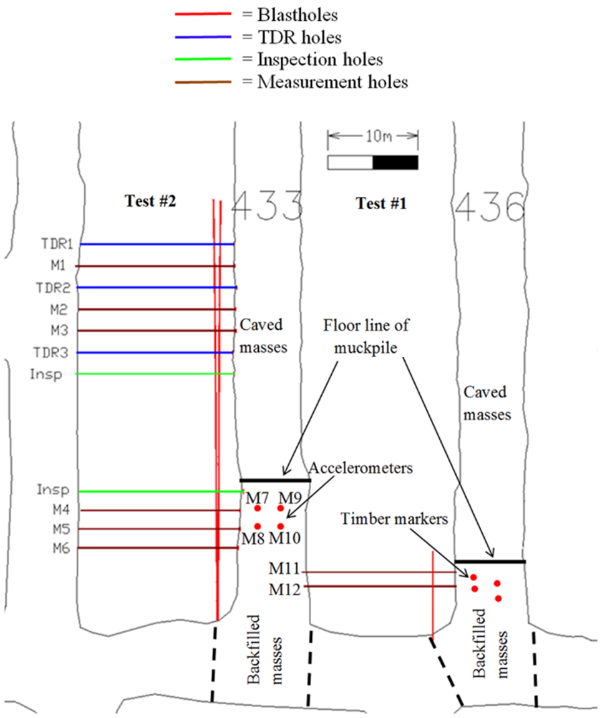

Figure 3 Experimental configuration of the 2nd pillar test (Petropoulos, et al., 2018).

The 2nd pillar test imitated the two middle blastholes of a production ring. The length of the boreholes in the 2nd pillar test was 45 m. The blastholes were charged with an emulsion that is used in production blasts, i.e. Kimulux R0500. The delay time between the detonation of the blastholes was zero, however, the absolute zero delay time had to be ensured. Hence, a detonation approach was developed by utilizing two equidistant twisted detonation cords (20 g/m) in each blasthole with a common initiation point for both blastholes. The main purpose of the zero-delay detonation was to move the burden as one slab, the movement of the middle part of the burden in the production ring. In this approach, the maximum compaction of the confining material could be achieved.

The displacement results from the measurement systems are shown in Figure 4. The dashed line denoted an extension of the model up to an arbitrary cut-off value. The implemented model was based on the literature Belen'kii, et al., (1969) and Barker & Mehta, (1993). However, the model was reformed by Petropoulos, (2017) and Petropoulos, et al., (2018) to fit the experimental data and became:

$$displacement = e^{a+b\cdot distance}$$

where the displacement is correlated with the burden movement and the sensors in the confining material, and the distance is the extent of the compaction zone by the burden movement. The parameters (a) and (b) are empirical coefficients. The analysis of the compaction results both from laboratory studies and the pillar tests showed that parameter (a) is dependent on the burden movement and the slope coefficient (b) can be correlated with the confining material characteristics, e.g. particle size distribution and moisture content.

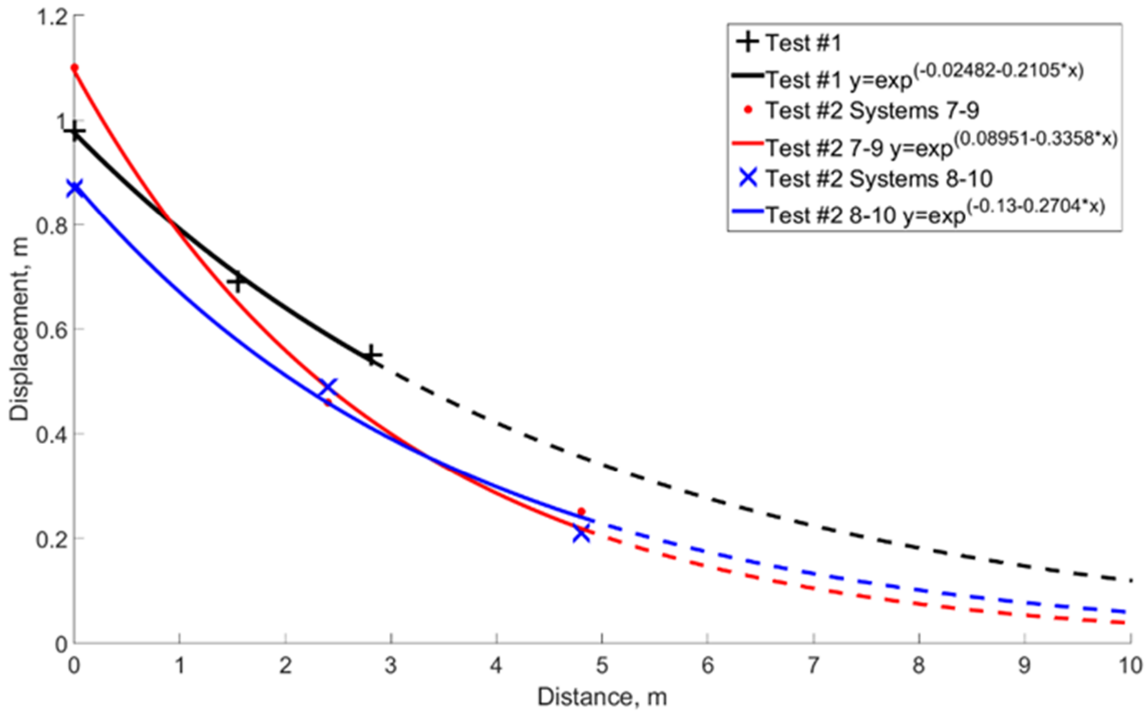

Figure 4 Displacement results of burden and instrumentation inside the confining material (Petropoulos, et al., 2018).

The burden in the 1st pillar (Test #1) moved approximately 1.0 m with a velocity of approximately 17 m/s and the burden from the 2nd pillar (Test #2) moved between 0.9 and 1.1 m with a velocity of about 10 m/s. The two values of the burden movement are due to the two measurement profiles in the confining material along systems M4 and M5 in Figure 3. The coarser confining material (Test #1) showed a larger compaction zone than that from Test #2 with the finer confining material. The burden displacements are very similar to the previous experiments done by Wimmer & Ouchterlony, (2011). In those pillar tests, there was no instrumentation in the confining material, then direct implementation of the model cannot be done.

The measured displacement of the burden resulted in a compaction of approximately 10 % in the confining material. However, in the caved masses, the measurements from the 3D scanner showed that the burden moved only 0.6 m which resulted in average compaction of about 5 %. The compaction of the confining material was calculated based on the volumetric change of the crosscut considering the cross-section of a measurement profile.

2.3 Pillar tests results

After removing the confining material up to the caved masses, the burden condition was revealed. Figure 5 shows the burden condition for Test #2 and several important observations can be made. The right image originates from the red box behind the blasted material in the left image, the red line shows the upper blasthole. The burden seems to be moved as one intact slab, as planned to maximize the compaction, however, it was heavily fractured, even if it appeared as intact. Behind the blasted material, a gap was formed and partially filled with burden erosion material. The burden erosion material is broken material from the separation between the blasted material and the intact rock. The material also originates from the vicinity of the blastholes. This gap can be related to chimney type flow paths that have been observed in studies done by Power, (2003), Sellden & Pierce, (2004) and Wimmer, et al., (2012). The burden erosion material is finer than that of the blasted material, the effect of this material in the gravity flow of the blasted material in a production ring is not known.

Figure 5 The condition of the burden after Test #2 (Petropoulos, et al., 2018).

During the mucking process in Test #2, the confining material was stuck on the surface of the burden indicating over-compaction. The over-compacted material has certain characteristics such as small particle size and moisture. The confining material in Test #2 was in a pendular state, i.e. moisture content less than 5 %. The rotation and relocation of the particles reduced the voids between the particles promoting the forces keeping the particles together. The over-compacted material could sustain itself on the surface of the burden, this indicates that a mechanical parameter was added in the material, it was apparent cohesion. Additionally, the change of the angle of repose after the blast at the vicinity of the burden indicates high frictional forces that contribute to the apparent cohesion. The introduction of apparent cohesion in a granular material alternates the flowing characteristics of the material. The particle size distribution did not show any change during the burden movement. Similar observations were made at the laboratory studies (Petropoulos, et al., 2017) when similar conditions were present. If such condition exists during the blast of a production ring, then a disturbance of the gravity flow might occur in the form of bridge forming temporary or permanent hang-ups. Finally, the mixing of the blasted material with the confining material was not observed in the pillar tests, this observation contradicts to what Kvapil, (2004) proposed for the interaction between the blasted and caved materials during a production blast.

The measurements and observations from the small-scale and pillar tests resulted in the conceptual model presented in a time-velocity graph (Figure 6). Slightly after the detonation of the blastholes at t_0, the burden starts accelerating up to the maximum velocity (t_1), although the burden has not reached yet its final position since there is the deceleration part until t_2. After t_2, the confining material reacts as a loaded spring by pushing back the blasted material until t_4. Additionally, the burden erosion material might be compacted as the burden moves backward. The burden erosion material was unlikely to be stabilized due to compaction because it is dry. However, in the case of a wet environment, the burden erosion material might create bridges, either temporary or permanent, between the blasted burden and the caved masses with flow channels in between them.

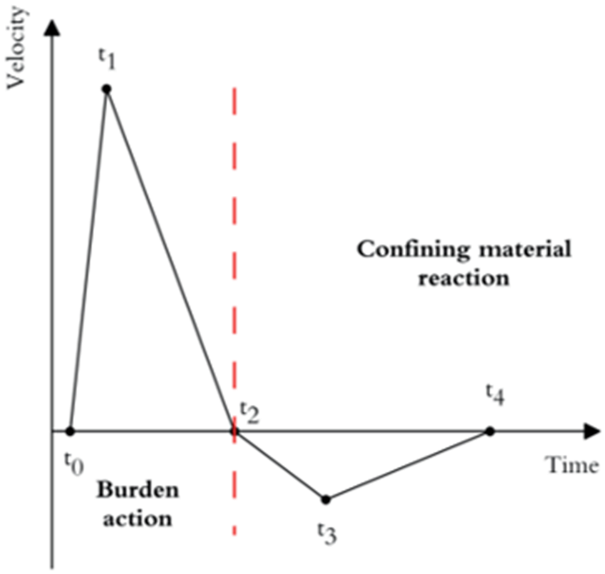

Figure 6 Conceptual model of the burden behavior during confined blasting (Petropoulos, 2017).

2.4 Full-scale test

The next step was to design and perform a full-scale test. The full-scale test was designed to monitor the burden behavior before, during and after the blast of a production ring. In other words, the full-scale test was designed to measure and observe the burden behavior in real conditions without any simplifications or assumptions. The experience and knowledge from the small-scale and pillar tests were valuable and used to design the full-scale test. The implemented instrumentation was improved based on its performance from the pillar tests. Some extra elements had to be designed for its installation.

The selection of the production rings was in cooperation with the smart marker tests that were performed at that time at -1051 m level and production block 26 (Wimmer & Nordqvist, 2018). Figure 7 shows the experimental design of the full-scale test. The complexity of the full-scale test was higher than that of the small-scale and pillar tests. Semi-horizontal boreholes were drilled from the production level above, i.e. -1022 m level. The length of the measurement boreholes was as long as 50 m, the main concern with these long boreholes was potential intersections with the blastholes and boreholes having smart markers, irregularities of the borehole wall and long-term stability of the boreholes. There were drilled 24 measurement boreholes for the installation of the different types of instrumentation. The measurement systems were modified compared with the instrumentation in the pillar tests to compensate for the irregularities in the boreholes and more accessories were developed to be able to grout the systems in the boreholes. The measurement boreholes were filmed, cleaned several times due to falling breakouts from the borehole walls and open cracks. The deviation of the boreholes was measured to adjust the length of the measurement systems to be installed at their defined location.

The installed instrumentation was based on accelerometers, potentiometric displacement sensors, TDR cables, and draw-wire sensors. Totally 19 measurement systems were installed due to collapsed boreholes. The measurement systems with accelerometers and draw-wires were installed only in one burden in each of the two pillars, i.e. pillar 270 (left rings) and pillar 272 (right rings). The systems with the accelerometers and the potentiometric displacement sensors were used to monitor the dynamics of the burden during the blast. The TDR systems covered 4 rings in each pillar. The TDR systems were used to monitor the rock mass movement as the blast front approached the monitored production rings. The location of the TDR systems was at the circumference of the rings to additionally detect the behavior rock mass at the boundaries of the rings. The systems with the draw-wire sensors were used to monitor the burden movement as well as the gravity flow of the blasted material towards the draw point. During the blast the initial movement of the wire was measured by high-speed cameras because the draw-wire sensors could not sustain the initial high accelerations, gravity flow was then monitored with the draw-wire sensors. Furthermore, cameras were used to generally monitor the progress of the functionality of the measurement systems, before, during and after the blasts.

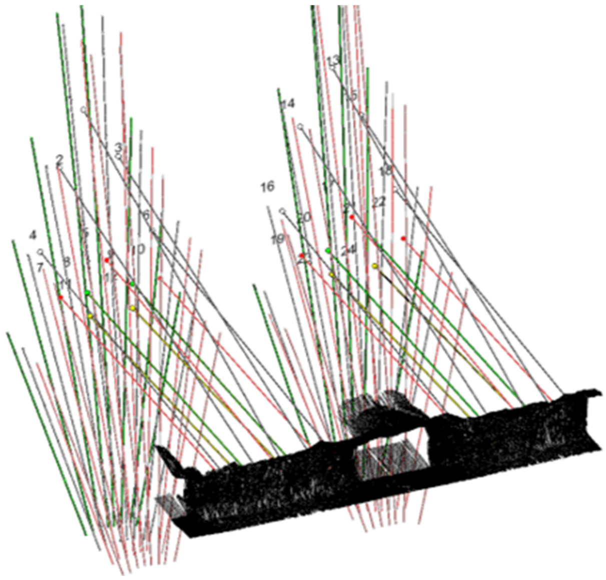

Figure 7 The experimental design of the full-scale test.

2.5 *Full-scale test results*

The displacement results from the accelerometers, potentiometric displacement sensors, and the draw-wire systems are presented in

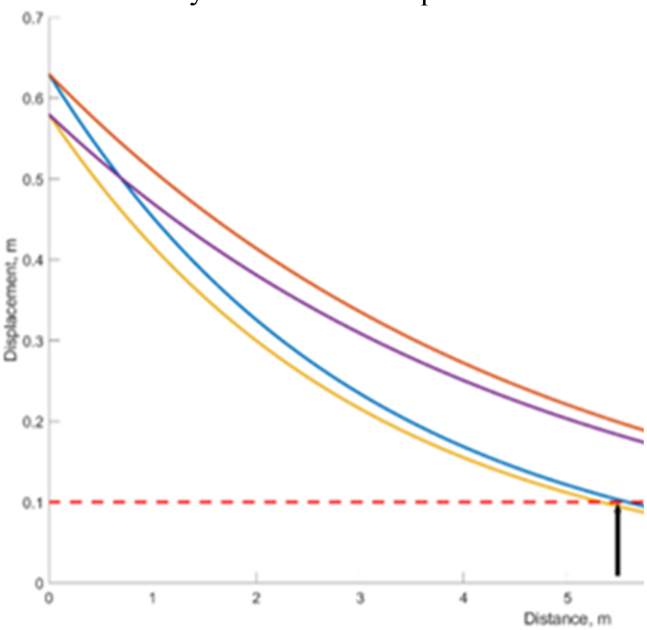

Figure 8. The burden moved with a velocity of approximately 10 m/s. The results showed that the burden started moving after 32 to 38 ms from the detonation of a neighboring blasthole. The burden moved approximately 0.6 m, e.g. the results from the draw wire systems were 0.58 and 0.63 m. The model used in the pillar tests results was implemented in

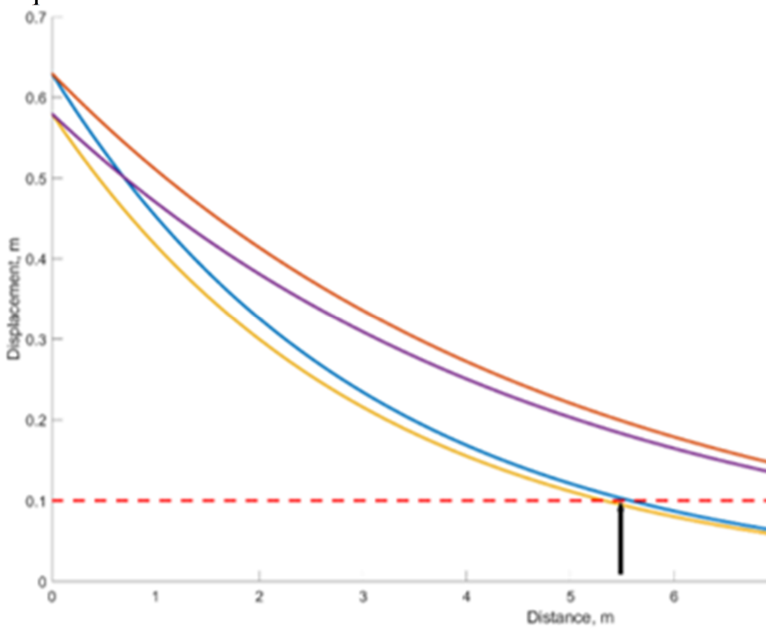

Figure 8 by using the measured displacements as initial values in the model. The main difference, here, is that the particle size distribution of the caved masses was not known, however, the confining materials in the pillar tests ranged from fine to coarse materials. The implementation of the model assumed that the confining material was fragmented (compressible) and there was no remnant pillar (incompressible material). Then, the slope coefficients from the pillar tests were used in the model implementation. Consequently, the extent of the compaction zone is presented as a range, varying from 5.5 (1st arrow) to 8.5 m (2nd arrow) for the range from fine to coarse caved masses at the vicinity of the measurement systems.

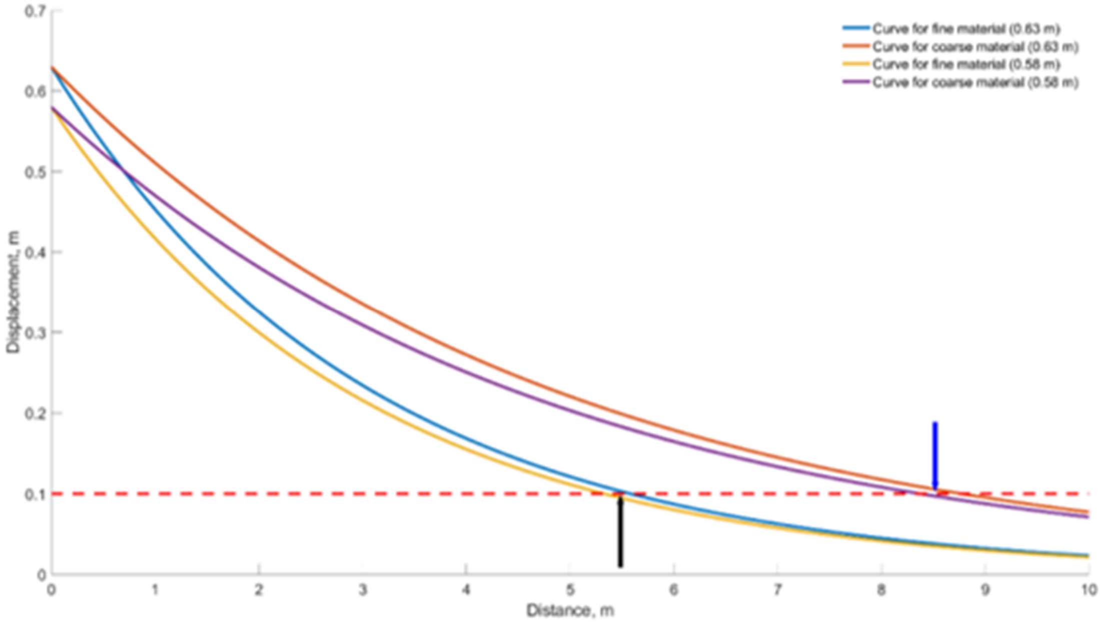

Figure 8 Displacement of the burden and particles in the caved masses.

Another significant observation was the monitoring of the gravity flow of the blasted material by the draw-wire systems in pillar 270 and in pillar 272. By contrast, the draw-wires in pillar 270 did not reach the draw point during the blast or the mucking process of the instrumented ring. However, there was a movement of the system during the blast of the instrumented ring. During the blast of the next ring, the system showed a movement. However, it was not possible to be quantified due to uncertainties since the movement was very large possibly caused by the inertia of the steel cable of the measurement system since the system was not fixed in position due to the previous blast. Very early at the extraction of the blasted material of the ring after the instrumented ring, a movement of the systems was detected. The very early detection of the systems indicates that there was an open gap between the blasted and the intact rock mass, similarly as in the 2nd pillar test. The systems in pillar 272, showed a different behavior, followed the flow of the blasted material toward the draw point.

The TDR systems showed an early movement of the rock mass due to the blast of the neighboring production rings. This type of blast damage is amplified as the blast front approached the monitored rings and its extent was up to 6 m. The geological structures in the vicinity of the rings might have a big role in the blast damage zone. The existing cracks might be activated or expanded by the blasts and causing the progressive mobilization of the rock mass. The breakage points were not detected immediately but the process started with minor movement which was detected as a minor shearing or pulling points on the TDR cables.

The cameras were recording during the blasts, especially for the last two blasts of the monitored rings to observe the behavior of the remaining instrumentation. Air blows were observed from the measurement boreholes during the mucking process. These air blows happened at 61 % of the extraction ratio. These air blows confirmed the speculated existence of temporary internal hang-ups during mucking. The temporary internal hang-ups are stoppages of the flowing material forming cavities that are not connected with the draw point and highly unstable. These hang-ups are formed when the blasted rock does not continuously flow as the material is mucked from the draw point, but it flows as material packages. This behavior was assumed by Hustrulid & Kvapil, (2008). The air blows were correlated with the mucking process and it was linked with iron ore content drops. The length of the measurement borehole was 39 m and the duration of the air blow was 20 seconds. The long duration of the air blow indicated a large open cavity in the blasted material. Furthermore, there were air blows that could not be related to any blast or mucking process, this indicates a slow-time mechanism. A potential mechanism behind these air blows is a type of creep mechanism that causes mobilization of hang-ups by, e.g. particle boundary sliding, particle dislocation, and rotation.

3 CONCLUDING REMARKS

All the above-mentioned experiments have revealed the dynamic behavior of the burden during the blast in confined conditions as well as the interactions between the blasted burden and confining material.

The small-scale tests, as well as the pillar tests, showed that the particles in the confining material rotate and relocate to build a strong enough skeleton to sustain the applied load by the burden. The existing fine particles, if there is moisture in the material, act as a bonding medium for the larger particles introducing apparent cohesion. The introduction of a new mechanical property in the material results in a total change of its flow behavior since it causes agglomeration. In addition, a mixing of the blasted and confining material was not observed. In pillar tests, there was no reduction of the particles size which shows that the kinetic energy of the burden applied on the confining material is enough only to compact it, and in some cases to over-compact, but it cannot breakage apart the particles. The pillar tests had many similarities with the full-scale test, in terms of burden movement and amount of explosives, then it can be assumed that there is no reduction of the particles size of the caved masses.

The full-scale tests revealed the burden dynamics in a real case scenario. The formation of temporary internal hang-ups and flow channels was confirmed and documented. The individual flow channels have been documented before by Power, (2003) and Wimmer, et al., (2012). The material that formed the bridges (a form of hang-up) might be the burden erosion or over-compact material. The compaction zone of the confining material by the burden movement can be as long as 2-3 burdens (3 m burden in the rings).

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