Proceedings of the NROCK 2023
The IV Nordic Symposium on
Rock Mechanics and Rock Engineering
ISBN 978-9935-9436-2-0
DOI 10.33112/nrock2023.8

Numerical Analysis of the Sensitivity of Joint Parameters to the Cross-cut in Response of Dynamic Loading

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ABSTRACT

Rock masses are far from being continuum and consist essentially of intact rock and discontinuities such as joints. Presences of discontinuities affects the propagation of the stress wave in rock mass. In this paper the impact of joints properties and features on the dynamic response of underground cross-cuts to seismic loading induced during dynamic large-scale field test in Kiirunavaara mine, was numerically investigated. The numerical methods used comprise the finite element code LS-DYNA and the 2D Universal Distinct Element Code (UDEC). The LS-DYNA model simulated the blasting and acquired the crushed zone and the vibration velocities around the crushed boundary. The vibration velocities from LS-DYNA were then used as an input velocity in the UDEC model. The studies of parameters such as joint normal and shear stiffness, joint spacing and joint orientation were conducted. The vibration responses at the wall of the underground cross-cut from UDEC were analyzed and compared to observed field test results. The results show that the normal stiffness has large effects on the peak particle velocity (PPV) while the shear stiffness contributes less influence. However, changes on joint space and orientation affect the PPV at the wall of the cross-cut. The joint stiffness explains the quality of the joint to transmit the stress wave while the joint spacing, joint orientation describe the blocky in burden which explain number of times the stress wave will be reflected before reaching cross-cut wall. The analysis can be useful during designing of the blast, burden as well as cross-cut support.

KEYWORDS

underground cross-cut; joints; numerical modeling; dynamic response

1. INTRODUCTION

The rock is divided in two categories: intact rock and rock mass, the latter is characterized by existence of discontinuities such as joints, faults, and other features. Sometimes rockmass can be subjected to dynamic events as earthquake or induced seismicity such as blasting, excavation at high depth etc. The disturbance induced by the dynamic events propagates in rock mass in the form of stress waves. The presences of the discontinuities affect the propagation of stress waves through the rock mass. Therefore, prediction and evaluation of wave attenuation or amplification across the jointed rock mass are vital components upon designing. These components are vital upon designing dimensions and orientations of underground cross-cuts, appropriate rock supports, time span as well as uses of the cross-cut. However, stress waves across the discontinuities (joints) experience complex phenomena that include multiple reflections, transmissions, refraction, superposition as well as absorption. Mechanical and spatial properties of the joints are vital factors that affect the wave propagation in the joints. The harm side of the stress wave propagation as rockburst in deep mines, collapse surface and sub-surface structures as well as damaged caused by it, has attracted researchers to study the wave propagation in jointed rock in different aspects, from theoretical, experimental and numerical point of view.

Perino et al. (2010) and Chai et al. (2017) performed theoretical studies that considered one joint set with parallel joints through rock mass model. The incident wave applied in one end and the reflected wave at the other end of the model. The number of the parallel joints altered, as was the space between the joints. Both models showed that the wave amplitude decreases as the number of joint increases. The increase in joint number increases delay time (phase), also the amplitude increases with the increase of the normal stiffness. The analytical study and quantification of stress wave propagation in the jointed rock mass widely use Displacement Discontinuity Model (DDM) (Schoenberg 1980, Pyrak-Nolte 1996). In that model stress is considered continues while displacement is discontinuous. In the other hand Ma and An (2008) performed numerical simulation of blast-induced rock fracturing where a finite element model was used to study the wave propagation through jointed model, in their model the orientation of the joint was changed and the focus were the type of damage that might be caused by the wave reflection on free surface. Huang et al. (2015) used the PFC2D code to simulate the propagation of stress wave in the filled joints since unfilled joints are not so common in presence. The fill material in joints including weathered clay, sand, silt etc, either saturated or unsaturated, has impact in mechanical properties of the joints. The simulation considered that the filled material has no tensile strength and therefore the reflected tensile wave will stop passing through and complex multiple reflections occur in layer of filled material. The work of Zhang et al. (2013) simulated the blasting as induced wave propagation in the jointed rock and its effects on the test site walls of tunnel. The numerical model used the coupling of LS-DYNA and UDEC, the former was used to simulate the blasting, and the latter was used to simulate the wave propagation in the jointed rock. UDEC coupled with 2D-AUTODYN model used by Chen and Zhao (1998) to study wave attenuation in blasted dry jointed rock mass. The modelling results showed that the presence of the joints in the rock mass causes rapid attenuation of the waves.
Numerical modeling must establish origin of joint. The joint origin may influence the wave propagation as it may affect the number of joints in given joints spacing. Therefore, this study took into consideration joint origins, joint stiffness, orientation and joint spacing.
Shirzadegan (2020) reported the large-scale dynamic field tests conducted in Kirunavaara mine in Sweden after reported cases of rockburst. The tests aimed to assess the capacity of rock support systems subjected to dynamic loading. Blasting was used to generate the seismic waves. The tests were also studied using numerical analyses (Shirzadegan, 2020). A combination of UDEC and LS-DYNA was used in the analyses. However, it was concluded that lack of certainty of mechanical and spatial values of joints. In this study the numerical modelling was carried out to investigate the sensitivity of joint parameters in wave propagation, severity of its damage in test wall performed based on large scale dynamic test 6 conducted in Kiirunavaara mine (Shirzadegan et al.,2016b). The LS-DYNA was used to simulate blasting and the UDEC was used to model the dynamic response of the test wall.

2. FIELD TEST AND NUMERICAL MODELING

2.1 FIELD TEST

The large-scale field tests were carried out in the Kirunavaara mine. The mine is located in the northern Sweden. The orebody strikes about North-South and dips 60° to the East. The orebody is estimated to be 4 km long with an average width of 80 m. The orebody lies between trachyo-andesite and rhyolite. The main mining method is large-scale sublevel caving (Malmgren, 2005). The tests were conducted in the northernmost part of the Kiirunavaara mine, block 9 and mining level 741 m. Seven tests were conducted (Shirzadegan et al.; 2016a and 2016b) in cross-cuts 93, 95, 100 and 103.
In Tests 1 – 5, the distance between the blasthole and the test wall was 2.8 – 3.9 m. Based on the results from these tests and numerical analysis by Zhang et al. (2013), the distance was increased to 8.1 – 8.7 m in Tests 6 and 7. In Tests 6 and 7 the blastholes were drilled in the middle of the pillar between cross-cut 100 and 103.

The holes were charged with NSP711 explosive, and the length of the charge was 10 m. The blastholes were not stemmed to reduce the effect of gas pressure. Shirzadegan et al.(2016b) mapped sixty five (65) joints in the site area. The mineralization and geology of the site are illustrated in Fig. 1

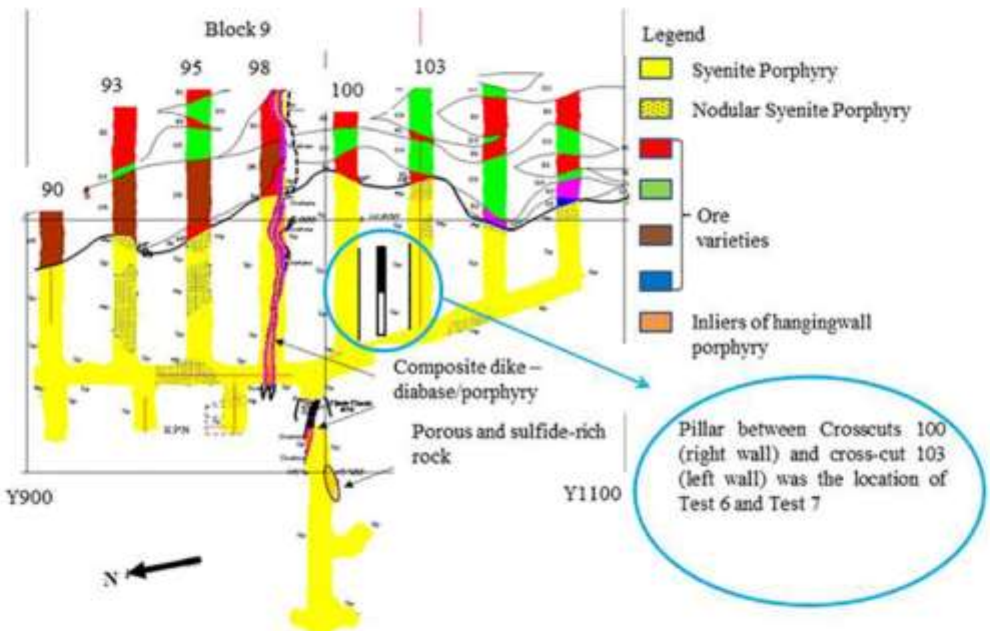


Figure 1: Location of the test site (Shirzadegan et al. 2016b).

2.2 NUMERICAL MODELING

According to Zhang et al. (2013) the explosion cannot be simulated using UDEC as the detonation creates a crushed zone around the blasthole that causes enormous energy absorption. Therefore, LS-DYNA was used to simulate the detonation stage of the blast. The NSP 711 explosive used in the field test is modelled with an explosive material model in LS-DYNA and with the Jones-Wilkins-Lee (JWL) equation of state (EoS) (Lee et al. 1968) as Equation (1):

$$p = A_1\left(1-\frac{w}{R_1V}\right)e^{-R_1V} + B_1\left(1-\frac{w}{R_2V}\right)e^{-R_2V} + \frac{wE}{V} \tag{1}$$

where:

p = the pressure;
A1, B1, R1, R2 and ω = constants
V = the specific volume
E = the internal energy.

A1, B1, and E have units of pressure while R1, R2, and w are unitless. The parameters of NSP 711 explosive were calibrated by Helte et al. (2006) and are listed in Table 1. In Table 1, ρe is the density of the explosive used, D is the velocity of detonation of the explosive, PCJ is the Chapman-Jouguet pressure of the explosive and Ee is the initial internal energy of the explosive.

Table 1.Properties of NSP 711 Explosive

ρ_e (kg/m^3)	*D* (m/s)	P_{CJ} (GPa)	A_1 (GPa)	B_1 *(GPa)*	R_1	R_2	*w*	E_e (kJ/cc)
1500	7680	21.15	759.9	12.56	5.1	1.5	0.29	7.05

A Crushed Zone Boundary (CZB) with a diameter of 1.1 m was obtained by the LS‐DYNA analysis and used as an internal boundary in UDEC. At the CZB the velocity-time history calculated by LS-DYNA was applied as an internal boundary condition in UDEC. The particle velocity applied at the CZB and the UDEC model are shown in Fig 2a. The UDEC model is used to simulate the stress wave propagation in the jointed rock mass.

The UDEC model of Test 6 was 80m x 80 m was built. The diameter of crushed zone boundary (CZB) was 1.1 m. The blastholes were drilled in the pillar between cross-cuts 100 and 103. Cross-cuts were 7 m wide and 5.2 m high.

History points in the model of cross-cut 100 were located on the test wall, 1.5 m above the floor (bottom), 2.2 m above the floor (middle) and 3.5 m above the floor (upper) in Fig.2a. Plastic deformation, wave propagation and running time considerations led to the zone size 0.2 m. The external boundaries of the model were located as far as about four times the dimension of the cross-cut and were set as non-reflecting (viscous) boundaries to address reflected waves. Fig 2a represents two joint sets UDEC model structure.

In this UDEC model the in-situ stresses used were based on the work by Malmgren and Sjöberg (2006) that considered mine-scale of the Kirunavaara mine. The adopted stresses are -16.48MPa and -11.28MPa in x and y directions, respectively. Since this paper reports a sensitivity study a base case was defined, see Table 2. One parameter at a time was varied while the other parameters were held constant and equal to the base case values. The input parameters for the mechanical properties of intact rock and mechanical properties of joints used in the Base Case are listed in Table 2 and Table 3 (Malmgren and Nordlund, 2006, 2008 and Brandshaug, 2009).

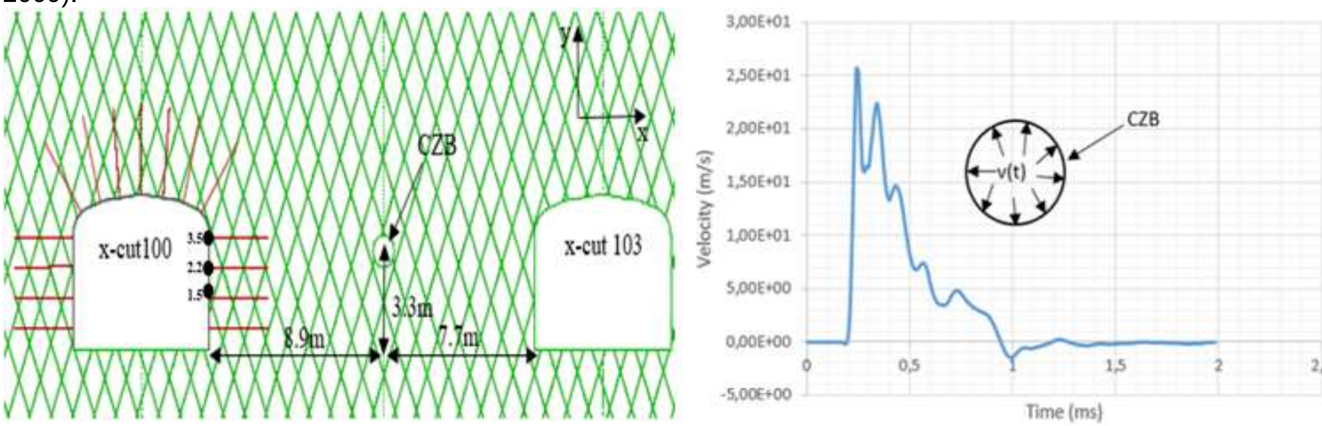


Figure 2: a)UDEC Model layout, b) Vibration velocity around the Crushed Zone Boundary

Table 2: Strength Properties of Intact Rock.

Density (Kg/m^3)	Elastic Modulus (GPa)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Friction angle (o)	Tensile strength (MPa)	Poisson's ratio
2800	70	50.7	27.6	31	61	16.5	0.27

Table 3: Parametric values of the joint.

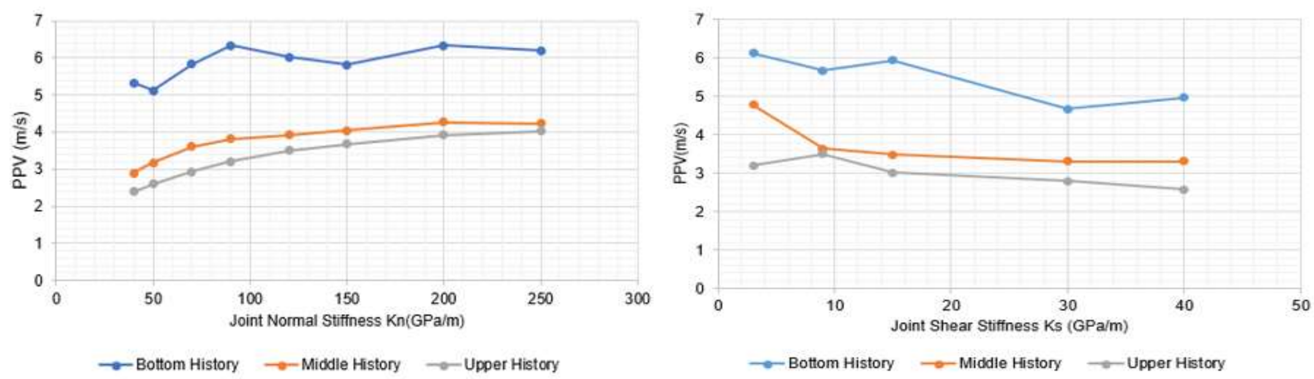
Parametric properties	Parametric values	Base case
Normal Stiffness (GPa/m)	40, 50,70,90,110,150,200,250	110
Shear Stiffness (GPa/m)	3, 6, 9, 11, 15, 20,30	9
Joint space (m)	1, 2, 3	1
Orientation of joint set ID 1 (º) ID 2 (º)	 100,115,130 51, 66, 81	 115 66
Joint Origin (m)	-1,-1 0,0 1,1	0,0
Cohesion (MPa)	N.A	0.5
Tensile Strength (MPa)	N.A	0.5
Friction angle (º)	N.A	35

3. RESULT AND DISCUSSION

This work aimed to numerically study the effects of joint mechanical and spatial behaviour on wave propagation based on large-scale field test. Histories points defined at the wall to monitor responses of the rock mass. The results are in displacement and peak particle velocity.

3.1 Effect of Joint Stiffness

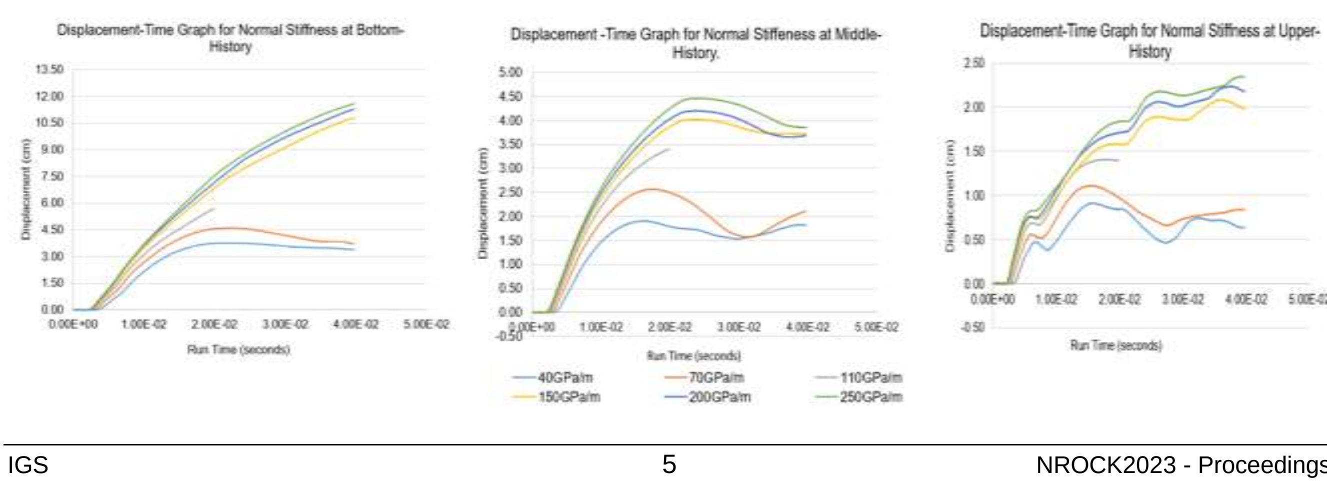
The normal stiffness is the slope of the linear elastic normal stress versus normal displacement curve recorded during normal compressive loading of a joint. The shear stiffness is the slope of the linear elastic part of the shear stress versus shear displacement curve recorded during shear loading.
Joint stiffness together with the other factors such as the poison ratio of the joint, angle and type of incident waves are the factors that control the magnitude of waves the transmitted, refracted and/or reflected at the joint.
The result showed that the PPV recorded by the history point in the model at the bottom (lowest point) are the highest and the history at the upper history point are the lowest. Furthermore, an increase of the normal stiffness led to an increase of PPV, but the increase of shear stiffness led to a decrease of the recorded PPV (Fig3). The simulation were made when joint stiffness changes while other joint parameters like spacing and orientation kept constant at the base case values.



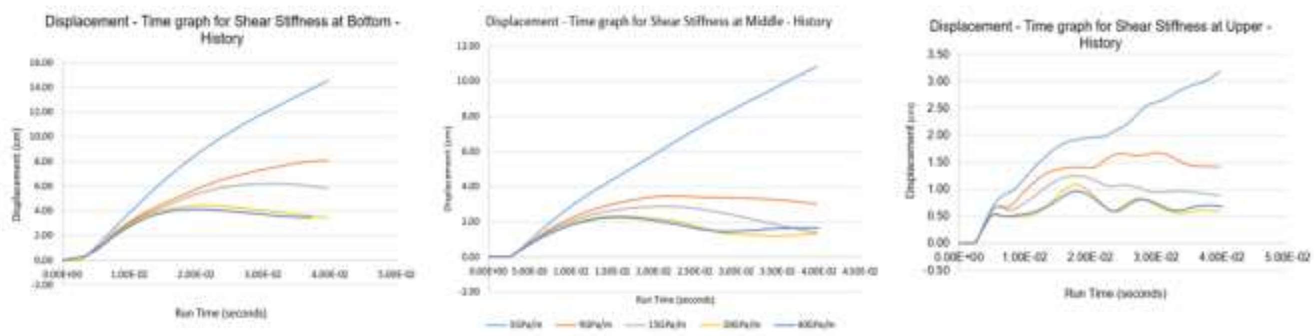
a) b)

Figure 3: PPV of history points due to changes in a) Joint normal stiffness b) Joint shear stiffness.

The displacement-time histories with different stiffness are shown in Figure 4. For some of the stiffness values the displacements show a peak, but for other stiffness values the displacements keep on increasing during the whole simulation time. The displacement in the upper point shows an undulation with time, which is not the case for the other two history points.
The displacement of the tested cross-cut wall increased as the normal stiffness increased. Models with low normal stiffness reached the peak faster than those with high normal stiffness. After peak, the displacement remained more or less the same until the end of the simulation (Fig.4a). When the shear stiffness increases to displacement increases, low shear stiffness model records larger displacement at the surface of the drift cross-cut than models with high shear stiffness (Fig.4b). The same trends as for velocity, the displacement at the bottom histories records large displacement and upper history small displacement.



a)



b)

Figure 4: Displacement – run time at histories points. a) Normal stiffness changes b) Shear stiffness changes

Velocity and displacement were increases as the joint normal stiffness increases but decreases as the joint shear stiffness increases. Modeling of stress wave propagation across joints shows that filtering of wave is less if the joint normal stiffness is high and vice-versa. This is because the normal stiffness of the joint determines to what extent the joint will open when incident stress wave crosses over. Pyrak-Nolte(1996) and Zhao(2014) shows that the transmission coefficient increases with increasing normal stiffness of the joint, however studies by Gu et al(1996) and Li(2013) showed that it is only possible if the incident wave is p-wave. The results of simulations are based on the P- incident wave that originate from CZB agree with Gu et al (1996) and Li (2013).

3.2 Effect of Joint Space.

The effect of joint spaces on the stress wave propagation was observed by monitoring ppv at the history points defined in the wall of the cross-cut. The results show that the PPV were higher for small joint spacings (1 m). The PPV decreased with increasing up to spacing to 3 m. When the spacing increases more. i.e., > 3 m, the PPV increases (Fig 5).

In these simulations joint spacing were changing but joint orientation and joint stiffness were kept constant to the base case values.

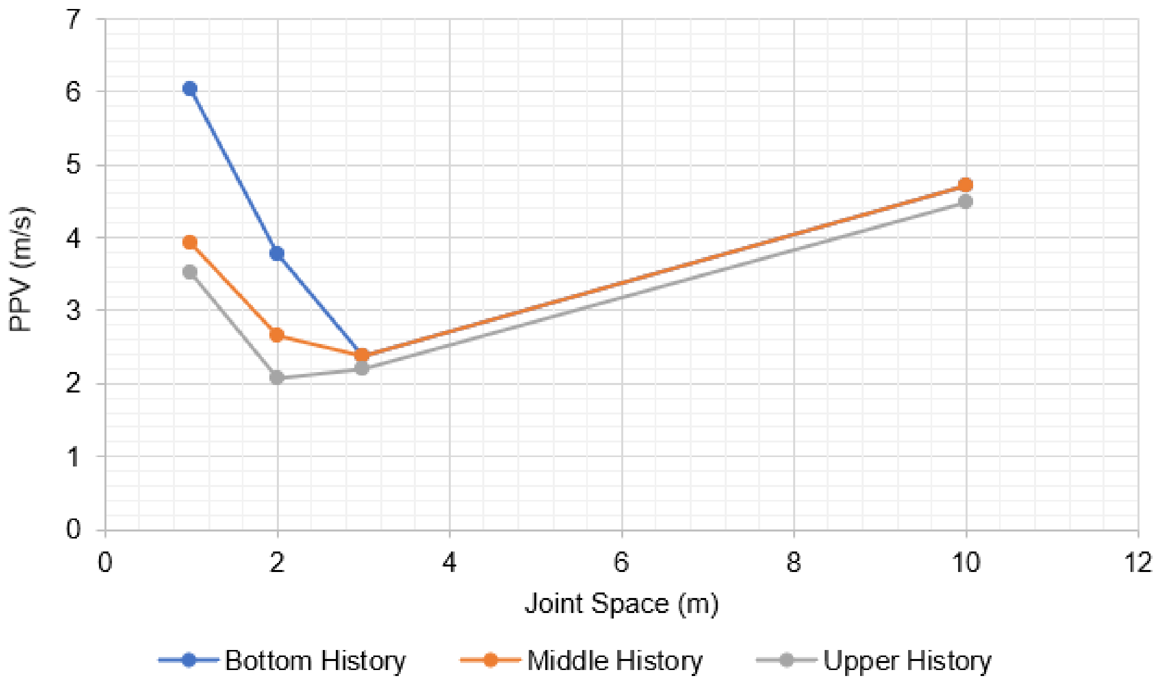


Figure 5: Velocity at the cross-cut wall with different Joint spaces

Tensile yield with different joint spacing is shown in Figure 6. For small joint spacing (1-2 m), the whole wall and the shoulder (for 1 m spacing) have yielded in tension. For the case of 3 m spacing, yielding has only occurred at mid height very loacal also with respect to depth from the surface. For the case of 1 m spacing there is almost no yielding in the centre of the burden. In the case of 2 m – 3 m, yielding has occurred in the middle of the burden, but these zones are located around the discontinuities in the burden. For the cases of 10 m and 14 m joint spacing, tensile yielding occurred in in the whole wall with several meters depth. Tensile “fractures” develop from the wall towards the CZB. For the joint spacing 10 m more “random” zones in the middle of the burden than in the case of 14 m spacing. When the spacing is 14 m the yielding is concetrated to the tensile “fractures”. For the intact rock yielding has occurred from the wall to a depth of several meters. The tensile “fractures” has propagated the whole way from the wall to the CZB (or vice versa). A conical volume of rock defined by the tensile “fractures” has developed.

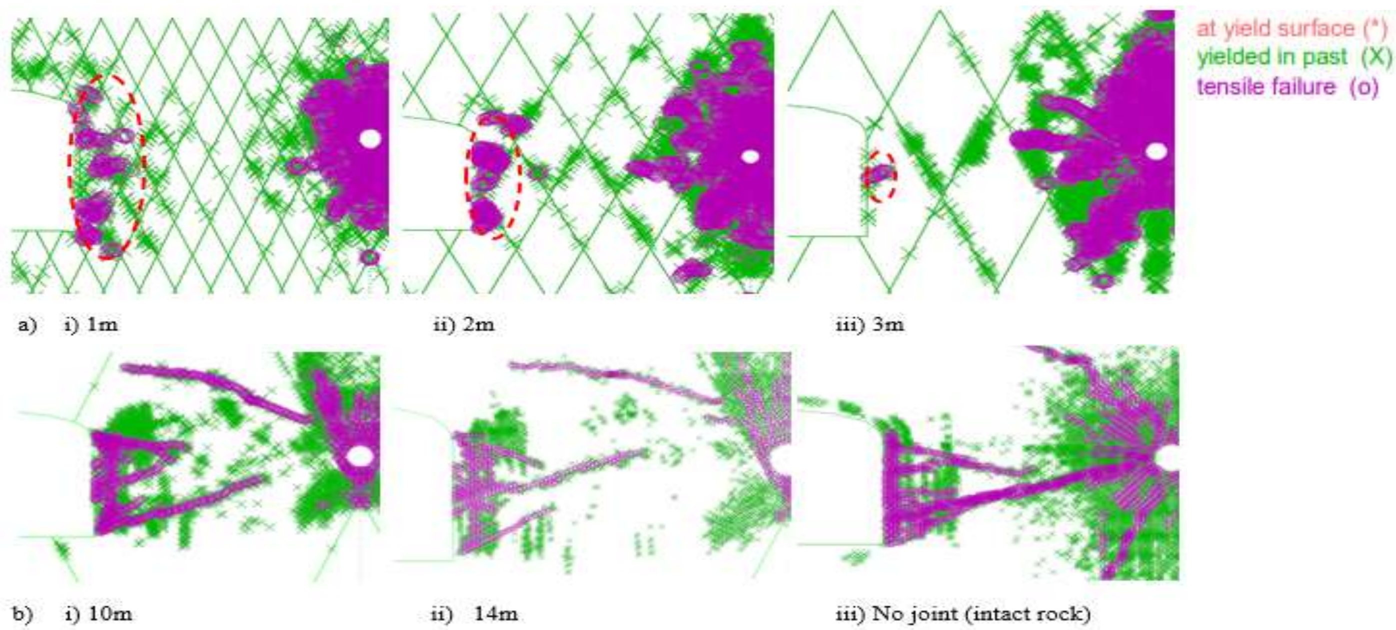


Figure 6: Tensile yield at different joint spaces. a) Joint spaces within the burden depth. b) Joint spaces large than the burden depth

Small joint spacing may result in many parallel joints within a small volume. This may lead to superposition of waves as result of multiple reflection. Part of the wave may be trapped between the joints resulting in attenuation of the wave or resonance (high amplitude). Zhu (2011) showed that in some cases the magnitude of wave transmission is increasing with increasing joint number which means small joint space in given domain. The wave propagation at joint space bigger than depth of burden (> 8.9m) crosses over single joint before reaching the cross-cut wall, this single joint is the result of locating the origin of the joint at the center (0,0) of the UDEC model during building up.

Heavily jointed as results of small joint space cause the rock to act as the intact rock hence thick depth of tensile failure.

3.3 Effect of Joint Orientation.

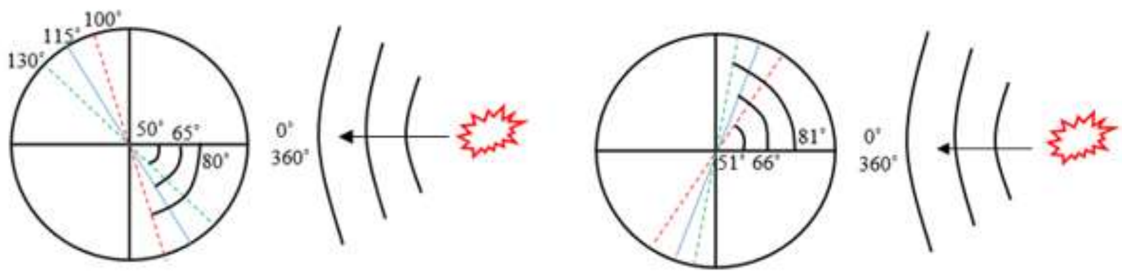
Four different models were analysed to investigate the effect of joint orientation. The orientation of one joint set varied while the orientation of the other joint set was kept constant. The orientation of the joint with varying orientation, was changed by 15(°) at a time. Parameters other than joint orientation were kept constant to base case values.

Joint set 1 (JS1) and set 2 (JS2) for the base case are oriented to 115 and 66 degrees respectively. The orientation of joint sets J1 and J2 are presented in Table 4. The values in the blue line in the table 4 were kept constant while the counter-value in grey were changing.

Table 4: Orientation of J1 & J2 that used in simulation.

J1	100	115	120	115	115	115
J2	66	66	66	51	66	81

The orientation of joint sets JS1 and JS2 makes more or less same angle to the incident wave except that are dipping in different directions (Fig.7). The changes of JS1 to 100˚ and 130˚ made about 80˚ and 50˚ to incident wave direction.



a) J1 b) J2

Figure 7: Direction and orientation of joint sets. a) J1 b) J2

The relationship between the PPV and the dip angle of both joint sets is shown in Figure 8. Figure 8(a) shows the case of 100˚ produces the high PPV compared to the other cases at all history points. For joint set 2, the case of 66˚ gives the high PPV compared to the other cases, see Figure 8(b). The possible reason is due to multiple transmissions and reflections of waves

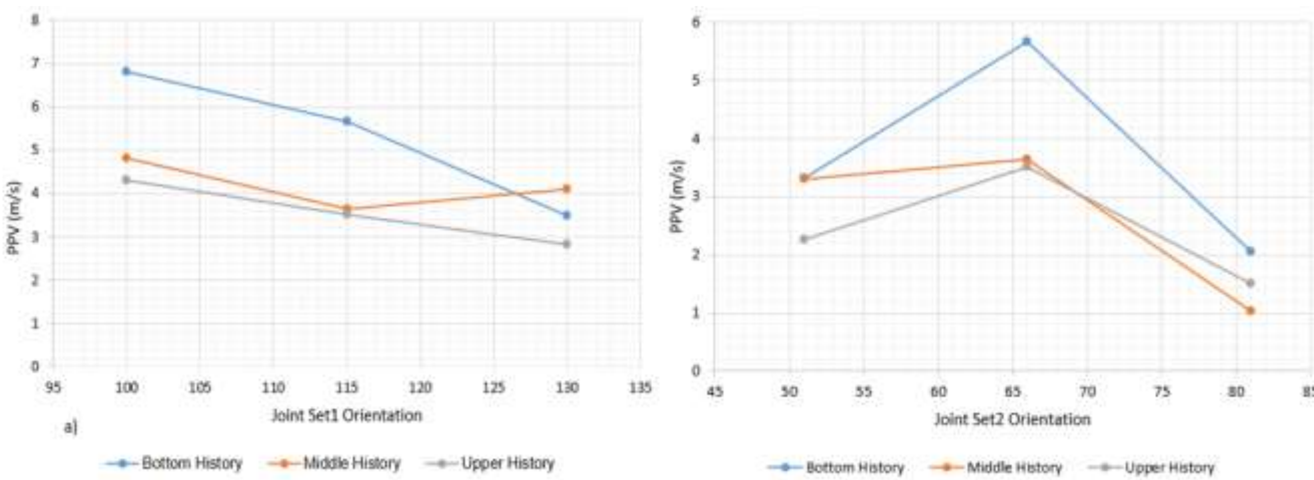


Figure 8: Velocity changes with Joint orientation changes, a) Joint set 1 b) Joint set 2

The depth of tensile yielding intensity around the tunnel wall corresponding to ppv recorded. Joint set 1 with 100˚ orientation has higher records of ppv and deep tensile yielding. The J2 orientation angles of 51 and 82 has low ppv records as well as shallow depth of tensile yielding in the cross-cut wall (Fig.9).

The orientation of the joint play vital roles in propagation of waves in the rockmass, the orientation of the joint determines at what angle the incident wave get to the joint medium. The extreme cases of transmission and reflection of the wave occurring when joint is perpendicular or parallel to the incident wave direction. Gu et al.(1996) analytical solution found that p-incident waves perpendicular to joint will result with very low rate of transmission and high rate of reflection of waves.

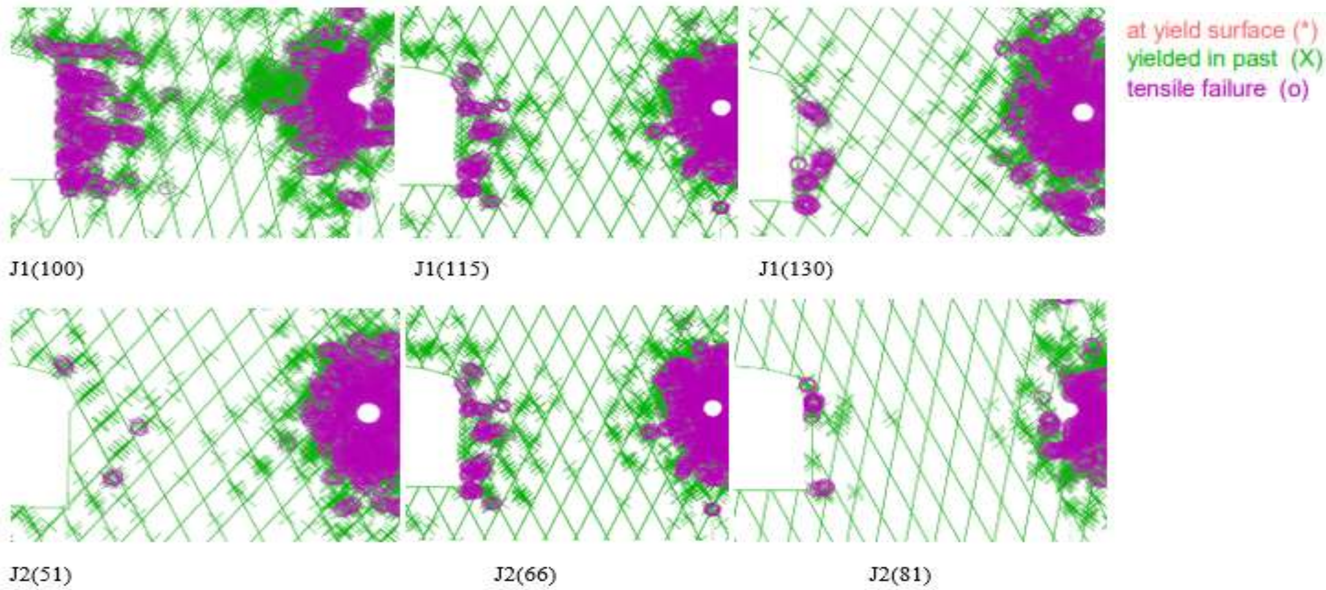


Figure 9: Tensile yielding around the cross-cut wall

3.4 Effect of Joint Origin

One of the joint parameters that has to be assigned a value in a UDEC model is the joint origin. It defines the coordinates of the point at which the first joint in a set starts. This means that depending on the joint origin, the joint will intersect the wall or not. If it intersects the wall, the position of the intersection affects the behaviour. One setup of joint origins of two joint sets can result in a wedge or not, it will also affect the deformation pattern of the wall (see Figure 10). In this case, the joint origins changed by shifted in either direction while other joint parameters kept constant to the base case values.

If the joint origin coordinate is (0,0), see Figure 10. If the joint origin is moved 1m to the left and one meter down (-1,-1), two wedges are formed without any kinematic constraints and can therefore be ejected if the reflected wave at the wall creates tensile stresses that exceeds the strength of the joints. For the case when the origin was moved from (0,0) with 1 m to the right and 1 m up a wedge is formed at the bottom of the wall.

The PPV at the surface of the wall shows that the model with joint origin at the center (base case; 0,0) has the highest PPV. In the two other cases shows lower PPV than that of the base case. The PPV for (-1,-1) and (1,1) are similar. For the base case the bottom point is significantly higher than that of the joints with origin at (-1,-1) and (1,1).

Tensile yielding in the models shows different pattern with different joint origin. The joint origin at the center (0,0) has tensile yielding at the wall of the cross-cut. Tensile yielding with possible ejection at the bottom of the wall, occurs for the base case. However, in the models with origin origins at (-1,-1) and (1,1) show similar trends, i.e., there was no tensile failure at the wall of the cross-cut, but tensile yielding occurred inside the burden(Fig.10b).

The low PPV and tensile yielding in the cross-cut wall for the models with joint origin (-1,-1) and (1,1), respectively, could be due to the two scenarios. Firstly, the obstruction at the blasthole. The waves from the source were not evenly distributed around the blasthole, even though the surrounding area is in the damage zone. The obstruction somehow increases the attenuation of incident waves and hence low ppv and low tensile yielding at cross-cut wall. Secondly, joint origin shifting changed the location of joint intersection to the cross-cut, changed distance of first joint close to blasthole and formation of wedges. The changes of joints interaction to cross-cut wall not only affects the resonance phenomena as a result of multiple transmission and reflection but also it affects stress regime around the cross-cut wall.

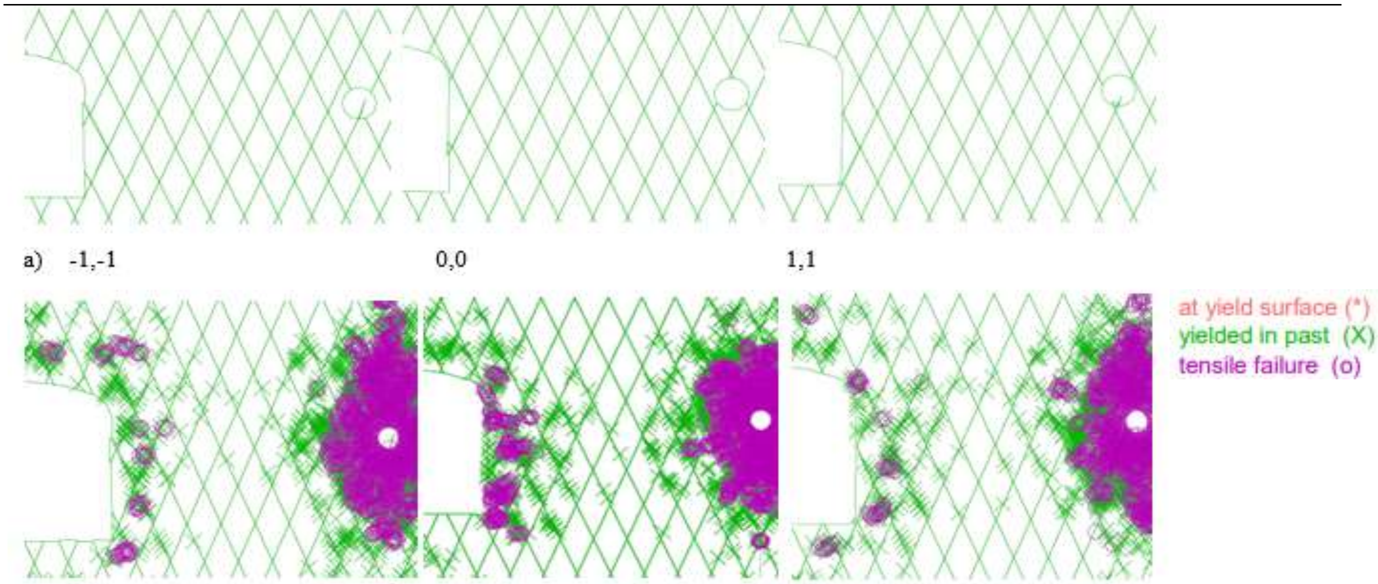


Figure 10: The model joints and tensile yielding.

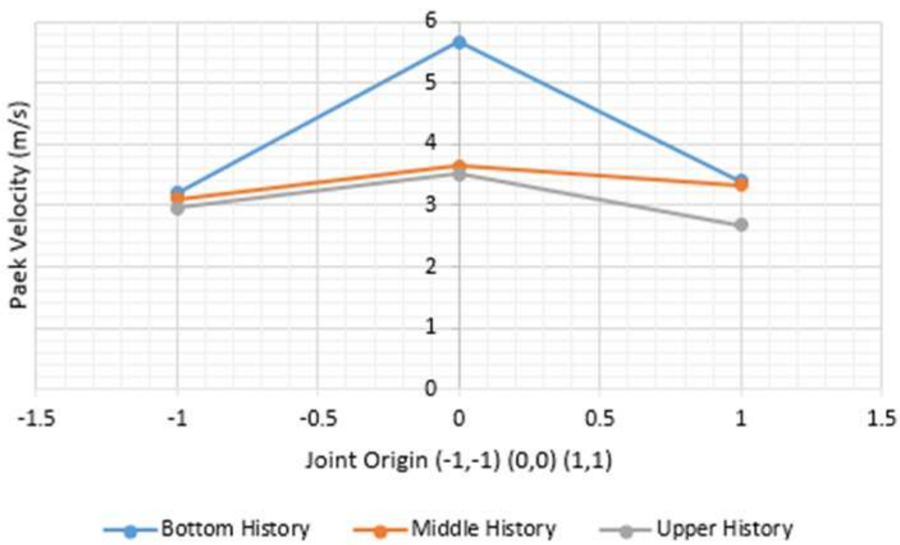


Figure 11: The velocity records at the surface of the wall

4. CONCLUSION

This work uses coupling of numerical models to simulate the influences of mechanical and spatial properties of joint on wave propagation and stability of the cross-cut. It has drawn the following conclusions

- Joint stiffness: The PPV shows an asymptotic behavior with increasing joint stiffness (both normal and shear stiffness). This clear for the middle and upper history points. The PPV in the bottom point shows a similar behavior, but the curve does not flatten out as for the other points. The PPV looks different for the bottom point, and does not reach an asymptote. It undulates around a PPV value of around 6 m/s. The PPV for the middle and upper points are similar, with a higher PPV for the middle point.
- ***Joint spacing:*** The PPV in all points at the wall show a similar behavior. The PPV in the bottom and middle points decreases when the spacing increases from 1 m. For an increase in spacing from 1 – 3 m, the PPV increases. The PPV for 10 m is almost the same for all points at the wall. The PPV recorded at the bottom of the wall shows the largest change with joint spacing of all the three points.
- ***Joint orientation:***

  - Joint set J1: At the bottom and the upper position the PPV decreases monotonically with increasing orientation. However, the PPV at the middle of the wall has a minimum at 115°.
  - Joint set J2; At all of the points the PPV has a maximum at 6 m/s, its minimum for 81° and the intermediate value for 51°.
- ***Joint origin***: The PPV has its maximum for joint origin (0,0). The PPV for the points (-1,-1) and (1,1) are similar.

It should be noted that the parameters in this study that are independent are the normal and shear stiffness and the spacing and the joint orientation. The joint spacing and the joint origin are coupled. For larger spacings the result will be very sensitive to where the joints starts. See for example Figure 6. The location where the joint intersects the boundary affect the behavior of the rock mass.

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