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Numerical investigation of the use of hydraulic stimulation to mitigate fault slip risk in deep mines

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Abstract

Fault slip and associated seismicity present a significant risk to the safety of underground mines. This paper investigates whether hydraulic stimulation, defined as the injection of pressurised fluid into a rock mass in advance of mining, has the potential to mitigate such risks. Fluid injected in the proximity of a critically-stressed pre-existing fault plane decreases the effective normal stress acting on the fault, initiating slip. Based on this concept, hydraulic stimulation could be used to trigger the release of built-up strain energy in advance of mining.

Numerical investigations are carried out in a two-dimensional distinct element code to model the effect of injection on the slip of a pre-existing fault located adjacent to a conceptualised open stope mining operation. Injection is accompanied by slip and a significant decrease in shear stress acting on the fault. When no injection is performed, excavation triggers a series of slip events in response to the changing abutment stresses, generating a maximum M_w 1.3 event. Conversely, when hydraulic injection is performed prior to the mine excavation sequencing, the total number of slip events is reduced, and a lower maximum magnitude of M_w 1.1 is observed. Longer injection durations are observed to trigger larger areas of slip and greater total shear displacements. However, a consequence of injection activities is that stress becomes concentrated outside of the fluid propagation front, potentially triggering seismicity in areas where it was not originally anticipated.

Keywords: *fault slip, induced seismicity, hydraulic injection, numerical modelling, rockbursts, shearing*

1 Introduction

As underground mines extend to increasing depths, brittle rock mass failure presents a significant safety risk to mine operations. One form of high stress failure, termed 'fault slip', occurs when underground mining alters the in situ stress regime present at depth, triggering the sudden, violent shearing of pre-existing discontinuities located adjacent to excavations. An understanding of the location and timing of fault slip rockburst events is key to mitigating the risk of harm to personnel, yet predicting such parameters with any certainty has proved difficult due to the complex mechanics driving such events.

Fault slip events are experienced frequently in deep mining regions worldwide, with a significant number reported at mines located in the Sudbury Mining District of Ontario, Canada. Yao et al. (2009) documented a series of slip events that occurred when mining towards a waste pillar at Copper Cliff North Mine, located in the footwall of the Sudbury Igneous Complex. The source of the events was determined to be a slip on a pre-existing structure in the pillar. Similarly, seismic events recorded at Garson Mine and Creighton Mine have been traced back to structural features located adjacent to active stopes (Malek et al. 2008; Bewick et al. 2009). The high stress environment in which these mines operate likely contributes to the number of slip events experienced. Many mines in the region extend to depths of greater than 1,000 m (Blake & Hedley 2003), and due to the tectonic history of the area, maximum horizontal stresses are nearly twice the magnitude of the vertical stresses (Malek et al. 2008). In addition, many mines in the Sudbury area employ open stoping extraction methods, such as vertical retreat and slot-and-slash mining, which result in the formation of large excavations that redistribute stress such that it concentrates in remaining pillars of intact material.

The research presented here aims to investigate whether hydraulic stimulation, defined here as the injection of pressurised fluid into a rock mass, has potential as a means of mitigating the risks associated with mining-induced fault slip. Two forms of stimulation can be distinguished: hydraulic fracturing and hydraulic shearing.

Hydraulic fracturing involves the injection of fluid under pressure for the purpose of generating new tensile fractures in previously intact rock. This technology is commonly used to improve the permeability of tight reservoir rocks, for example for shale gas extraction (Warpinski et al. 2009) and enhanced geothermal system projects (McClure & Horne 2014), as well as for cave inducement and fragmentation control in block caving operations (van As & Jeffrey 2000; Catalan et al. 2012). Hydraulic fracturing has also been investigated as a means to mitigate rockburst hazard by reducing the stiffness of the rock mass in critically stressed areas and redistribute stress away from active mining advances (e.g. Kaiser et al. 2013; Gambino & Harrison 2015).

Hydraulic shearing, on the other hand, involves the injection of pressurised fluid to trigger slip on pre-existing discontinuities. In this case, the increased fluid pressure reduces the effective normal stress acting on a critically-stressed discontinuity until it slips via the Mohr–Coulomb shear failure criterion:

$$\tau \geq (\sigma_n - p_f) \tan \phi + c \tag{1}$$

where:

- τ = the shear stress acting on the fault.
- σ_n = the normal stress acting on the fault.
- p_f = the fluid pressure within the fault.
- ϕ = the friction angle of the fault surface.
- c = the cohesional strength of the fault surface.

Like hydraulic fracturing, this can also serve to improve the permeability of tight reservoir rocks through fracture dilation and permanent gains in fracture aperture through self-propping (Preisig et al. 2015). In the context of rockburst mitigation, Board et al. (1992) conducted a hydraulic shearing injection trial in an attempt to trigger slip on a major fault in the Buffelsfontein Gold Mine in South Africa. Initial numerical modelling showed that injection at constant pressures along the length of the fault could trigger displacements and, theoretically, relieve built-up stress along slipped regions. A field-scale trial confirmed that small-magnitude ($M_L \leq -1$) events were triggered as a result of injection on the fault. However, the time-dependent stress behaviour resulting from the injection could not be assessed; it was unclear whether the stress changes acting on the fault were temporary or permanent, and whether far-field stress changes could be observed in response to the injection. Nevertheless, there is some evidence in the literature that hydraulic stimulation can cause stress relief. Mills et al. (2004) measured field-scale stress changes that resulted from hydraulic fracture propagation that would have also been accompanied by hydraulic shearing. Preisig et al. (2015) demonstrated through numerical models the stress shadow effects that develop around pre-existing fractures that open and slip in response to fluid injection. However, the ultimate effectiveness of hydraulic stimulation in achieving permanent stress redistribution remains unclear.

This paper will present preliminary results from research investigating the ability of fluid injection and hydraulic shearing to relieve stored energy concentrated along a critically stressed fault. It is hypothesised that hydraulic stimulation offers a means to trigger fault slip and, thereby, release built-up stresses along the fault in advance of mining. Doing so would help to reduce the frequency and severity of slip events, and reduce the likelihood of events occurring unexpectedly when personnel are present.

2 Methodology

A modelling study was conducted using UDEC version 6 (Itasca Consulting Group 2010), a two-dimensional (2D) distinct element code, which computes the displacement response of a jointed rock mass under various loading conditions. The rock mass is modelled as a series of discrete, deformable blocks separated by through-going discontinuities. The blocks behave as a continuum in which deformations are computed using a finite difference algorithm. Full dislocation between blocks is permitted through block contact relationships that allow for discontinuity opening/closing and shear (i.e. fault slip) through a Coulomb slip criterion. UDEC also has the ability to simulate fluid flow through discontinuities via a coupled hydro-mechanical algorithm, allowing the effects of hydraulic stimulation to be modelled.

For the current investigation, a static analysis is conducted to model the effect of both mining excavation and fluid injection on the behaviour of a persistent, through-going fault. Since this investigation focuses on hydraulic shearing of a pre-existing discontinuity, rather than the creation of new fractures, the fault is the only structure explicitly included in the model. The remainder of the rock mass is treated as an elastic continuum, hence the behaviour of other rock mass structures, such as minor joints and fractures, is not considered.

Transient, compressible flow is used to model fluid migration along the fault plane. This algorithm simulates fluid flow between adjacent domains on the fault based on a cubic law relationship:

$$q = -k_j\, a^3\, (\Delta p / l) \tag{2}$$

where:

q = the flow rate.

k_j = a joint permeability factor.

a = the hydraulic aperture of the fault.

Δp = the pressure difference between adjacent domains.

l = the domain length.

Note that, because the blocks are impermeable and no additional rock mass structures are explicitly modelled, the flow only occurs within the fault. In reality, significant amounts of injected fluid will leak off into the surrounding rock mass, reducing the pressure and volume of water contained within the fault. However, for the purposes of this analysis, this effect is not considered. Because of this, injection rates and migration times along the path of the fault are not expected to match those encountered in reality. The slip response under a given fluid pressure, however, will still hold true, allowing the fundamental behaviour to be modelled correctly.

2.1 Model setup and geometry

Numerical simulations are conducted to model the influence of two mining scenarios on a persistent fault that dips at 45°. Both scenarios involve the sequential excavation of a vertically-dipping, tabular orebody that strikes parallel to the fault. The orebody is mined via longitudinal open stoping techniques. The stope geometry and excavation sequence is shown in Figure 1, and is designed based on simplified versions of stope geometries encountered at Creighton, Garson, and Copper Cliff Mines located in the Sudbury region. Stopes are 15 m wide by 30 m high, and are separated by 5 m thick sill pillars. Access drifts are contained within the sill pillars but are not explicitly modelled, due to their assumed limited influence on model behaviour. After excavation, stopes are backfilled prior to excavation of the next stope in sequence.

It is worth noting that since the UDEC models are 2D plane strain analyses, the geometry shown in Figure 1 is assumed to extend infinitely in the out-of-plane direction, resulting in the injection 'point' being modelled as a line of injection extending out-of-plane. By the same logic, the excavation is modelled as an out-of-plane tabular feature. This is a reasonable approximation for excavations in orebodies where mining extends across a greater length parallel to the strike of the orebody than perpendicular to it. However, it is unrealistic to assume that each stope will be excavated instantaneously, as a series of blasts will likely be required to excavate the entire length of the stope. To account for this, stopes are excavated by reducing the internal pressure acting on the walls of the stope in stages until the final condition is reached. After each reduction in pressure, the model is allowed to come to equilibrium.

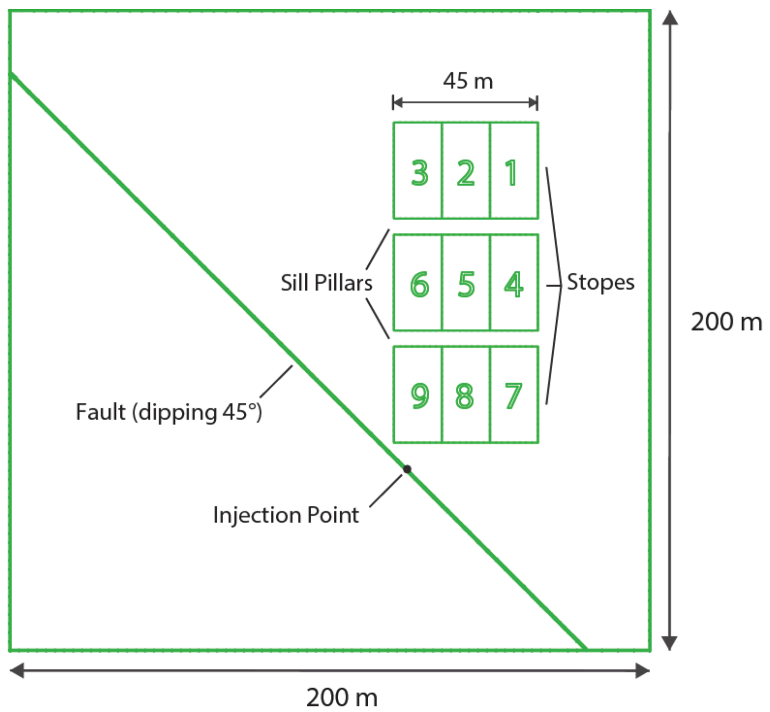

Figure 1 Cross-sectional view of the UDEC model showing mine and fault geometry. Numbered stopes indicate the order of excavation

In order to evaluate the effect of hydraulic stimulation on fault slip, in this case hydraulic shearing, two scenarios are modelled. In the first scenario, the entire orebody is excavated in the sequence shown in Figure 1 without injection taking place. Displacement on the fault is monitored after each excavation step to determine if a slip event has occurred. In the second scenario, the excavation sequence progresses until just before the slip, such that the fault is in a critically-stressed state. At this point, hydraulic injection is performed directly on the fault at the location shown in Figure 1. Once injection is completed, the remaining stopes are excavated and the slip response is compared to the first scenario.

2.2 Input parameters

Model properties are set to resemble those typically encountered in the Sudbury region. Parameters are derived from actual field data when available; otherwise they are chosen based on values found in the literature (e.g. Cundall & Lemos 1990; Zangeneh et al. 2013; Preisig et al. 2015). A complete list of input parameters can be found in Table 1.

The rock mass behaviour adjacent to the fault is assumed to be elastic, with properties typical of a diorite or granodiorite. For simplicity, the orebody and host rock are assumed to have the same elastic properties (reported here as bulk and shear moduli). Note that the input values are lower than typical intact rock values to account for the fact that the overall rock mass stiffness will be reduced by the presence of joints and other discontinuities that are not explicitly modelled. The backfill is modelled as an elastoplastic continuum with a yield strength defined by the Mohr–Coulomb yield criterion. Fault behaviour is modelled via the Coulomb slip criterion. A reduced residual friction angle value is assigned to the fault after slip; the purpose of this is to simulate the strength loss resulting from the shearing of asperities during slip. Prior to injection, the rock mass is assumed to be unsaturated.

Hydraulic injection is simulated at a point intersecting the middle of the slipping segment of the fault at a rate of four litres per second (per out of plane metre) for a period of eight seconds. This is followed by a shut-in period of four seconds in which no injection occurs. The fault is then allowed to drain completely prior to commencing the excavation step that triggers slip.

Table 1 Input parameters used in numerical models

Rock properties		Backfill properties		In situ stresses	
Density, ρ (kg/m³)	2,700	Density, ρ (kg/m³)	1,000	Depth (m)	2,000
Bulk modulus, K (GPa)	35	Bulk modulus, K (GPa)	0.4	σ_1 (horizontal, MPa)	101
Shear modulus, G (GPa)	20	Shear modulus, G (GPa)	0.5	σ_2 (horizontal, MPa)	74
		Friction angle, ϕ (°)	25	σ_3 (vertical, MPa)	55
		Cohesion, c (MPa)	0		
Fault properties		**Fault flow properties**		**Fluid bulk properties**	
Normal stiffness (GPa/m)	60	Permeability, k_j (Pa^{-1} s^{-1})	83	Density, ρ (kg/m³)	1,000
Shear stiffness (GPa/m)	60	Residual aperture (mm)	0.02	Bulk modulus, K (GPa)	0.1
Peak friction angle, ϕ (°)	38	Zero stress aperture (mm)	0.7	Gravity (m/s²)	9.81
Residual friction angle, ϕ (°)	30				
Cohesion, c (MPa)	0				
Tensile strength, T_0 (MPa)	0				

2.3 Seismic magnitude calculation

Seismic magnitude of mining-induced slip events can be calculated based on the seismic moment, M_0, a property that is defined by the following relation (McGarr 1994):

$$M_0 = \mu A D \tag{3}$$

where:

μ = the modulus of rigidity, approximated here as the shear modulus of the rock mass.

A = the area of the slipping surface.

D = the average shear displacement experienced during slip.

Given the 2D nature of the fault model, a circular slip surface with a diameter equal to the slip length is assumed. The moment magnitude, M_w, can then be approximated using the following empirical equation, where M_0 is measured in N·m (Hanks & Kanamori 1979):

$$M_w = 2/3 \log M_0 - 6 \tag{4}$$

3 Results

Modelling results for the two scenarios previously described were examined to determine the stress and shear displacement response along the fault at various stages of excavation.

3.1 Model response to excavation

As mining progresses deeper towards the fault, stress begins to concentrate in the remaining intact rock segments surrounding the mined out areas (i.e. abutments). In the later stages of excavation, this effect results in a region of decreased normal stress and increased shear stress forming along the fault segments located below the lowest working stope, as shown in Figure 2. By the time stopes 8 and 9 are excavated, the stress concentrations that interact with the fault are such that the frictional shear strength of the fault is exceeded and slip occurs. Figure 3 shows the total shear displacement generated on the fault as a result of this mining sequence.

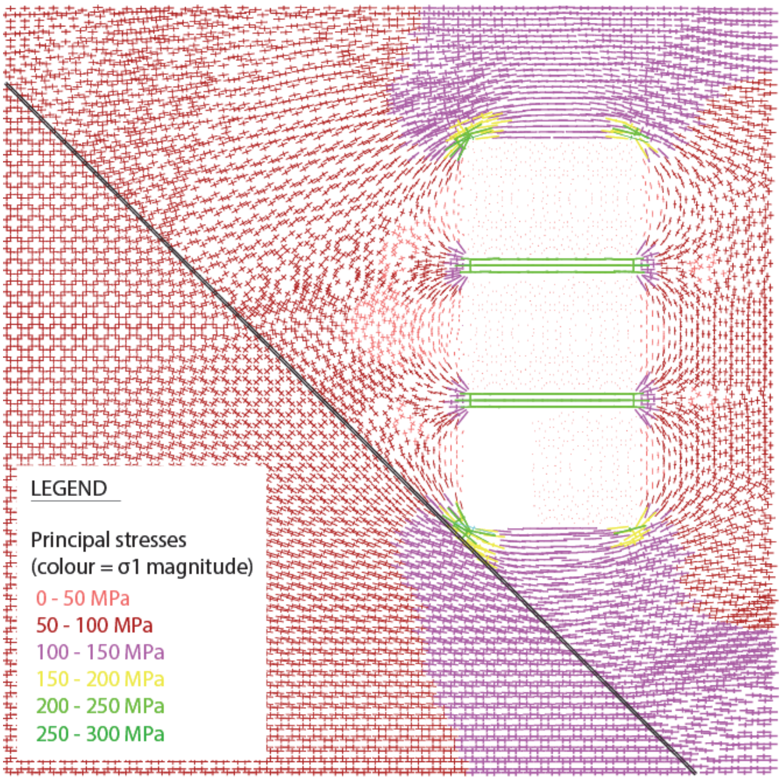

Figure 2 Principal stresses after excavation of stopes, without hydraulic injection. Stress concentrations can be observed at the corners of the lower excavation, which serve to trigger slip on the fault

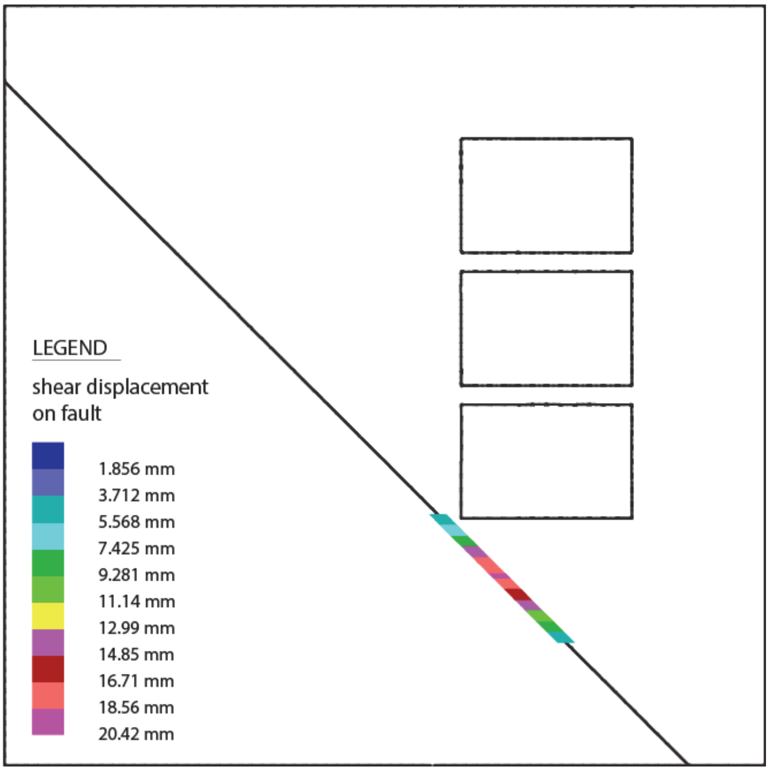

Figure 3 Magnitude of fault slip triggered with mining of all stopes, without prior hydraulic injection

By examining how shear stress and shear displacement on the fault change over time, we observe that a series of slips occur on the fault, beginning when stope 8 is excavated (Figure 4). Prior to this point, the sequential excavation of the model caused the shear stress acting on the fault to incrementally increase.

Eventually the induced shear stress exceeds the strength of the fault; when this happens, a sudden drop in shear stress occurs, coupled with a sudden shear displacement as the fault slips. In Figure 4, this is observed to occur at the beginning of the stope 8 excavation, as well as five more times during the excavation of stope 9. The timing of each slip appears to be triggered by each incremental excavation stage. Since the model reaches equilibrium after each period of displacement, each of the observed slips is considered to be a separate seismic event. It is interesting to note that the stress changes that accompany each excavation step in Figure 4 closely resemble stress cell measurements of seismic events recorded at Coleman Mine by Yao et al. (2016) in both shape and magnitude. This increases confidence in the validity of the fault slip behaviour simulated by the model.

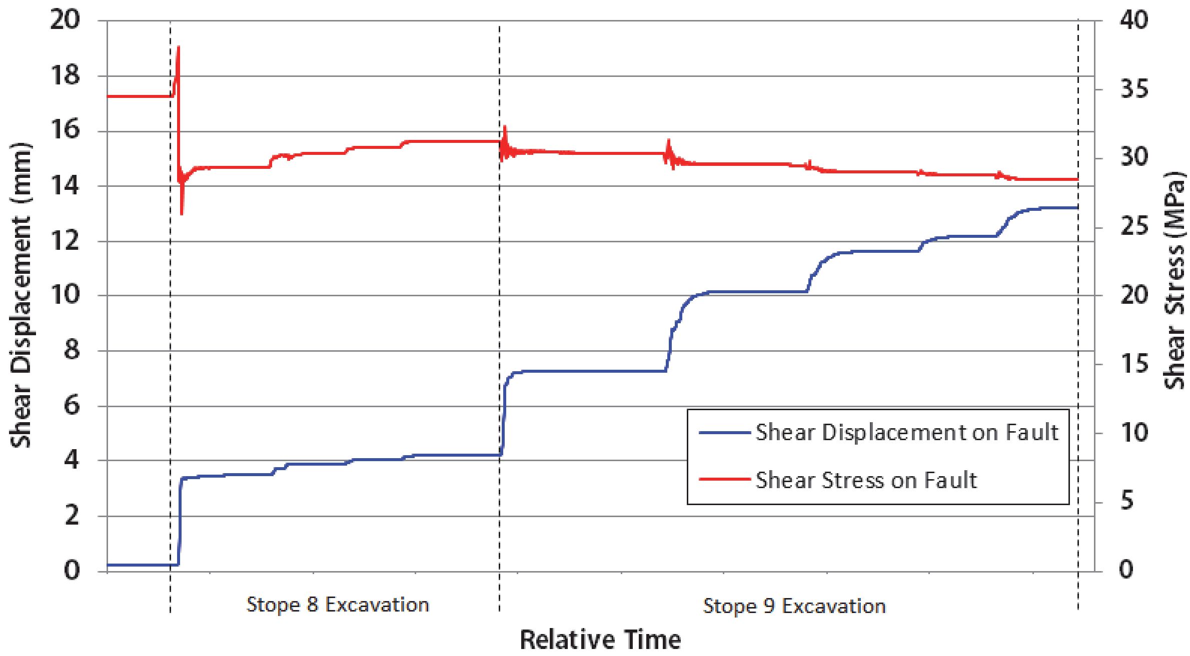

Figure 4 **Time history of shear stress and shear displacement for a representative monitoring point located on the fault. Histories corresponding to the excavation of stopes 8 and 9 are shown (no injection was conducted in this scenario). Slip events are observed as sudden stress drops coupled with shear displacements on the fault**

Using Equations (3) and (4), the maximum moment magnitude of slips induced by mining can be calculated. The largest seismic event occurs during the excavation of stope 9 and had a magnitude of M_w 1.3, while the first slip event triggered during the excavation of stope 8 had a magnitude of M_w 0.8. These values correlate well with maximum fault slip event magnitudes documented in the literature for the Sudbury region, which range from 0.8 to 4.0 (Malek et al. 2008; Snelling et al. 2013).

3.2 Effect of injection on fault slip behaviour

In the second modelled scenario, injection is conducted prior to the excavation of stope 8. Observing the time histories of shear stress and shear displacement changes (Figure 5), we see a number of similarities to the excavation-only scenario. Shortly after injection, the effective stress drops suddenly and slip occurs. Shear displacement on the fault continues until injection stops. After this point, the pore pressure is likely not high enough to keep the fault in a critical state and movement stops.

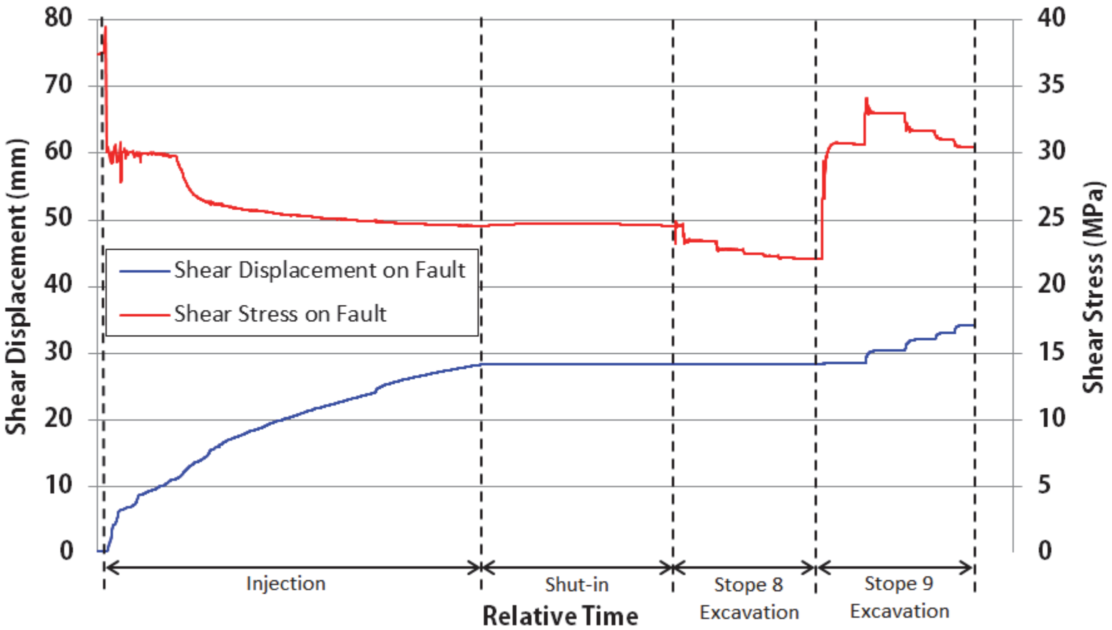

Figure 5 Time history of shear stress and shear displacement following a hydraulic stimulation treatment, for a representative monitoring point located on the fault. Histories correspond to the injection period, shut-in period and subsequent excavations. The injection is shown to result in a significant decrease in shear stress acting on the fault

It is interesting to note that following the hydraulic stimulation treatment, excavation of stope 8 no longer triggers a slip event as it did in the non-injection treated scenario. This indicates that hydraulic stimulation was at least partially successful at relieving built-up stress on the fault in advance of mining in this simulation. That being said, the stress reduction accompanying injection appeared to be short-lived, since the stress acting on the fault returned to nearly pre-injection levels upon commencing excavation of stope 9. A series of small slip events could also be observed during this final excavation stage. The maximum moment magnitude of these events was slightly reduced from the case without injection; the largest slip event was calculated as M_w 1.1 in the final excavation stage for the post-injection case.

4 Discussion

The results previously presented indicate that a significant release of strain energy accompanied the simulated fault slip events triggered by both excavation and hydraulic injection. The key difference is that when triggered by excavation only, this release is largely uncontrolled and, therefore, may occur unexpectedly when personnel are present in the area. In the conceptual mining scenario investigated, hydraulic stimulation in advance of mining is observed to trigger a more controlled release of stored strain energy in the area of interest; slip is initiated in the targeted area shortly after injection is started, and appears to halt when injection stops. Since a drop in shear stress accompanies slip triggered by injection, hydraulic stimulation treatments could be effective at reducing the stresses driving potential future slip events in advance of mining. However, because stress was observed to return to nearly pre-injection levels during the excavation of stope 9, a single period of injection may not be enough to relieve built-up stress as mining progresses. Although this may be partly due to the assumption of elastic rock mass behaviour, injection activities may need to be ongoing to account for future excavation stages that serve to further increase the stress acting on the fault.

An additional concern of pre-triggering slip via hydraulic stimulation is that the stress released on the slipping fault segments is transferred to adjacent portions of the fault. In the model, areas of the fault where slip was triggered display a reduction in shear stress (e.g. the behaviour shown for the monitoring point in Figure 5), however, adjacent areas that did not undergo slip during the injection phase experienced increased shear stresses as a result of injection (observed for other monitoring points in the model, but not shown in Figure 5).

This effect could potentially lead to increased seismicity occurring in areas beyond the extent of the fluid propagation front, as elevated shear stresses would bring the structure closer to failure. This is particularly problematic as it would imply the slip hazard may not be eliminated by hydraulic stimulation treatment, but merely transferred to other areas of the structure.

The duration of injection is also observed to have an effect on fault slip. Figure 6 shows that longer injection times result in an increase in maximum shear displacement on the fault, as well as a larger overall slip area. This is most likely a result of fluid propagation in that longer injection times force fluid further away from the injection point. Hence, increased injection durations may be more effective at triggering strain energy releases over large areas as the seismic moment triggered by the injection is directly proportional to the shear displacement and area of slip (Equation (3)). However, it should be noted that not all of the energy released by the shear displacements shown in Figure 6 takes the form of seismic energy. It is well recognised that the majority of the stress acting on a slipping fault is released aseismically, with the portion of energy available for generating seismic events defined by the seismic efficiency (McGarr 1999). For injection-triggered slips, where the release of energy appears to occur over a longer period of time than excavation-triggered slips (Figure 5), the radiated seismic energy could very well be smaller, or at least be distributed over a longer period of time so as to cause less violent movement in the surrounding rock. The static model created for the current analysis cannot accurately simulate the dynamic response resulting from fault slip events. Hence, a more computationally-intensive dynamic model will be considered for future evaluations.

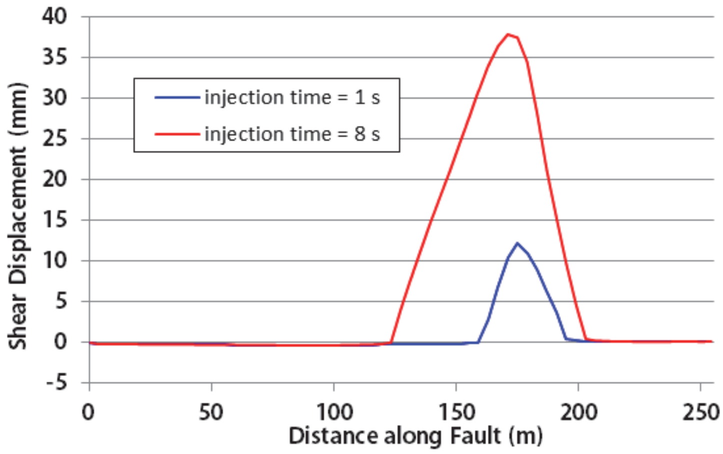

Figure 6 Magnitude of shear displacement at various distances along the fault as a result of injection for 1 s versus 8 s. Longer injection times trigger a greater maximum shear displacement as well as a larger area of slip on the fault

It should be noted that the current investigation does not consider fluid leak off or slip occurring on secondary structures, such as joints. This is significant as one of the risks of hydraulic injection is that fluid propagates beyond the extent of the fault undergoing treatment and triggers movement on structures that would not have slipped otherwise. This effect has been modelled on structures located many tens of metres away from the injection source and can occur long after injection has stopped (e.g. Zangeneh et al. 2013).

5 Conclusion

A numerical investigation was conducted to determine whether hydraulic stimulation could be used to initiate slip on pre-existing fault structures prior to mining, thereby reducing the risk of fault slip events causing harm to personnel. Results suggest that the injection of fluid in the proximity of a critically stressed fault can trigger a release of stored shear stress and strain energy acting on the fault. Excavations carried out after hydraulic stimulation treatment displayed a reduced frequency and magnitude of fault slip events compared to the case where no stimulation treatment was applied. However, a possible consequence of pre-triggering slip via injection is the transfer of stress and seismicity to other areas that originally were unlikely to slip.

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