Modeling of mining-induced seismicity migration

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ABSTRACT: Mining-induced stress changes during excavation are generally associated with rock mass displacements, which are enhanced by chains of rotations of discontinuous rock mass blocks. These may lead to rock mass slip along pre-existing discontinuities or fracturing intact rock. As a result, seismic events not only occur in the rock mass near the boundaries of mine excavations but also migrate further away at the mine wide scale, in deep underground mines. The latter type is more problematic and may be destructive to mining production due to their apparently unpredictable characteristics. A novel approach, the Channel Element Model (CEM), based on rock mass displacement and chain-like rotational movement, is introduced in this paper. CEM is a mathematical method, with which to model rock mass time dependent and remote interactions from source disturbances, in contrast to mechanical contact interactions by DEM, or constitutive relations by FEM to model near source disturbance responses. *Keywords*: Channel Element Model; Rotation; Shear; Seismicity migration; Modeling

1 INTRODUCTION

1.1 *Seismicity and energy flow*

Seismic events are generated by fracturing intact rock or slip along pre-existing discontinuities (Ortlepp, 2000). At continental scale, the tectonic movement causes the stress concentration, once the concentrated stress exceeds the local strength, an earthquake occurs, suddenly displacing at a significant distance and releasing the accumulated strain energy (Reid, 1910; Scholz, 1990; Kostrov & Das, 1988). The tectonic movement is an ongoing process with which the stress concentration accommodates. Reid (1910) proposed the elastic rebound theory after the 1906 California earthquake, which found the basis of earthquake/seismic cycling theory, characterized the relation of earthquakes and tectonic movements. At a mine wide scale, when the highly stressed rock volume is excavated, the supporting stress to the surrounding is removed, the movements are introduced due to the unbalances, which lead to stress field changes. In the unfavorably concentrated area, it may lead to rupture, i.e. seismicity. Furthermore, the seismicity creates dynamic loading on the remnant rock mass, which reinforces the remnant rock mass movement, may lead to a severe rock burst (Ortlepp, 1998).

The general relationship between seismic activities and mining operations in deep level mines has been well established by Cook et al. (1966). Salamon (1968) used a linear elastic model of a tabular operation to calculate the mining-induced energy changes with the mining-induced stress field, onto which the original undisturbed static equilibrium stress field is superimposed to form the final stress field. He regarded that the energy change is the work done by the face closure of the openings. However, when we account for the work done during rock mass convergent movement to the openings, the far end stress field does more work to the remnant than that released by the openings face closing. The remnant rock mass has two boundaries, openings faces and far ends, the former release the energy of the remnant rock mass, while the latter receive it. So that the actual energy change is a gain, not a release, in the remnant rock mass. If we consider the above is a dynamic process, the release is a trigger that initiates the energy flow, the energy flows from far ends to openings, heterogeneous and discontinuous nature of rock mass makes the energy flow structure unevenly distributed on site, exhibiting a network structure, called channel element network in this research. In ideal cases, a 2D circular or 3D sphere opening with hydrostatic stress at the far end, the work done by the far end two times of the energy of release by the opening face closing (Brady & Brown, 1993), so that the total energy gain in the remnant rock mass is equal to the amount of the energy release during the face advancing of the opening. Cook (1963) and McGarr (2000) introduced a rockburst energy budget: the released energy (actual energy gain) is equal to sum of aseismic deformation, seismic radiation, frictional slip and seismic events. Seismic radiated energy only accounts for 2% of the total release, frictional slip and seismic events consumes most part of the energy. With regard to the relationship between mining and induced seismicity, Cook's (1963) results indicating a tight coupling between face advance and seismicity, has been confirmed many times over in more recent studies using monitoring technology that is vastly more sophisticated.

However, the energy budget did not account for the internal energy flow of volumetric strain energy to deviatoric strain energy and uneven energy flow structure. Enlarged deviatoric stresses, lead to shearing, is a major factor, and the heterogeneous energy flow structure is another major factor, contributing to rupture in rock mass. We are trying to model the mining disturbance migration in the identified energy flow structure, so as to model seismicity migration in this research.

1.2 *Seismicity and instability*

Cook (1965) set a basis for Energy Release Rate (ERR) approach that violent fracture of rock occurs when an excess energy becomes available during the post peak deformation stage, also regarded it as an instability problem. Linkov (1994, 1996, 2000) developed a concept with an interplay process of softening and creep with which it is bifurcated at some point, either continuing softening and creep, or fracturing as an excess energy available. The softening and creep process could be in volumes or in contacts, as well as for the instability process, the rupture. The instability presents as a violent jump that is embedded in the overall material movements.

ERR sets a general relation between mining excavation and seismicity. ERR concept linked seismic/rockburst with fracture mechanics, in which fracture criterion is either Griffith's (1921) free surface energy, stress intensity or J integral (the integral of the external work done on the crack tips). They are all equivalent in fracture mechanics on linear elastic basis, the brittle fracture mechanism could be described as one of the three fracturing modes or their combinations proposed by (Irwin, 1957). However, Mode II or shear is the only form of rock mass rupture at depth that leads to large scale deformation (Scholz, 1990; Ortlepp, 1997).

Due to the discontinuity and heterogeneity at all scales of rock mass (Cook, 1994), even under high compressive stress condition at depth, tensile stress still initiates cracks, which weakens the rock mass strength (Diederichs & Kaiser, 2004). Underground excavation causes stress field rotating and changing (Kaiser, 2000), so that the maximum shear stress resulting from $\sigma1$ and $\sigma3$ may sweep to the weakest plane, leads to fracturing or slip, or make the maximum tensile stress exceed the strength at the tips of micro cracks, and after initiated cracks coalesce, resulting in spalling or bulking. Larger shear fracturing or slip is a coalescence of smaller failures, which are physically weakest parts corresponding to the stress field and their linkages build up major failures (Freudental, 1968).

1.3 *Modeling of mining-induced seismicity migration*

The energy relations, the rupture regimes above concluded a comfortable understanding of mining-induced seismicity. However, we still have no means to know where and when a seismic event may occur while conducting mining. This research, through studying the physical phenomena of mining seismicity at mine wide scale, maps the energy flow structure to a network which is embedded in rock mass, linking it with a phenomenological model, Channel Element Model. The network is identified by seismicity clustering induced by historical mining activities, the mining disturbances are expected to travel in it, obeying calibrating phenomenological behaviors.

2 MINING-INDUCED ROCK MASS MOVEMENT

Mining-induced stress changes by excavations are always associated with rock mass displacements, which may lead rock mass to slip along pre-existing discontinuities or fracturing intact rock. As a result, seismic events occur and migrate in the rock mass, shown in Figure 2-1.

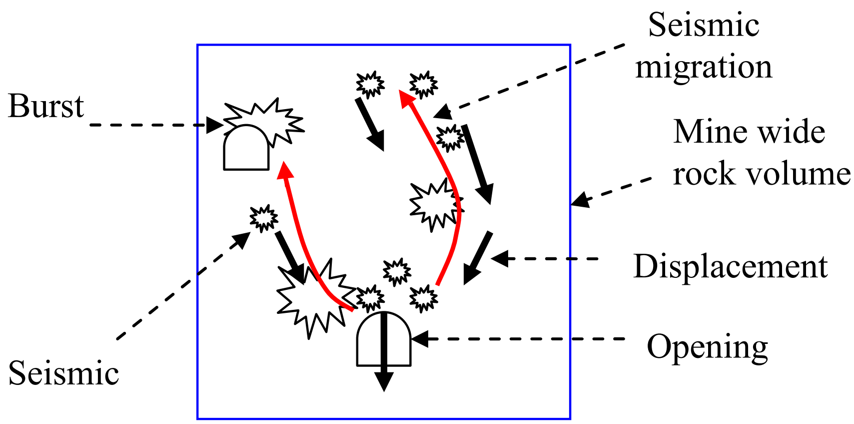

Figure 2-1 Seismic migration in rock mass.

McKinnon (2006) observed that the majority of seismic events occur close to excavation boundaries, but a certain amount of seismicity also occurs far away from mining excavations and appeared to be uncorrelated in time and space with mining activities, so called chaotic seismic events.

Near opening boundaries, stress field changes and rotates based on geometrical setting of openings and joints, unfavorable stress conditions may appear to initiate slip/fracture and leads to seismic event (Kaiser et al., 2005). With appropriate calibration of rock mass strength, numerical stress analysis can be used to estimate the extent of fracturing and therefore the extent of near excavation seismicity (Beck et al., 1997; Potvin, 2001; Beck & Brady, 2002).

Kaiser et al. (2005) stated when the excavation ratio increases in a mining block, a deformation induced by an underground excavation provokes a redistribution of local stresses, but more importantly, creates a displacement boundary condition change that leads to a rearrangement of massive blocks that make up the rock mass, called “mining Domino effects”

At a mine wide scale, the exact geometrical conditions of rock mass are never known (Kaiser et al., 2005), which introduces the significant uncertainties, to the Domino effects movement. As a matter of fact, any discrete element model derived from a subjective assumption of block configuration could not draw a right solution to rock mass movement at a mine wide scale.

Rock mass is a collection of blocks tightly fitted as three dimensional mosaics (Goodman & Shi, 1985). Under certain disturbances, e.g. excavations, some blocks are critical or sensitive, easily deviate from initial equilibrium state so that gear into a chain of movement. Moreover, their slight variation in shape could dramatically change its degree of stability, either turn into a stable state or a violent movement. Glaser & Doolin (2000) said: It is clear that not all discontinuities play equal roles in the behavior of rock masses. Physically minor discontinuities and geological features may sometimes be more critical to a design than major (larger) features. These minor features, however, are often overlooked. From a practical point of view, it is not clear what represents a critical or major feature, and it is often determined in a very subjective manner.

Muller (1966) stated that the properties of jointed media depend much more on the linkages between discontinuous systems than on the substance of the rock. The first important factor is discontinuous systems, the joint geometrical layout; the second one is mechanical properties of the joints. This is a perspective statement either in static view or in dynamic view.

In jointed rock mass, it is clear that key blocks proposed by Goodman & Shi (1985), no matter big or small, are movable to an adjacent disturbance, an opening or a seismic event. A sequential movable blocks may form a motion chain in rock mass. However, block instability is directional, so that the movement may present channeling effect at a scale which is much greater than the block sizes. The channeling paths may connect into a network in which the mining disturbances migrate.

3 DISTURBANCE AND STABILITY

Through tectonic movements, rock mass in the crust of earth experienced varieties of damages and deformations, locked in certain stress conditions in the ensemble of broken and deformed rocks, which built up a system instability condition at a site. The stress condition and jointing geometries may coincide unfavorably, forming a systematic instability, or a marginal equilibrium condition, mostly shear conditions.

A disturbance, a mining excavation, is an external factor adding on to a rock mass system. The interaction between the system and the disturbance is mutually dependent, it is not a stationary relationship, and may turn into a dynamic moving sequence, so that:

A disturbance could trigger a violent motion in the system, such as an opening, may generate a rock burst at a site.

A disturbance could change the system stability condition on a site, although there is no breakout at the time, the degree of instability is increased, making the system vulnerable to the coming disturbances.

A disturbance may be locked in a limited area, like an opening in continuum elastic material under compression, the system localize the disturbance by converging movement, creating arching effect.

A disturbance could migrate in the rock mass, it may attenuate by resistance or even enhance by breakouts it triggered. When travels in the rock mass, it got more chances to meet the critical conditions in the system; also its traveling changes the degree of system stability, presenting as disturbed rock masses.

A disturbance migration could be as fast as wave propagation; it may cause an instant breakout at a distance.

A disturbance migration could be as slow as creep movement; it may cause time delayed breakouts remotely since its creation.

In the engineering point of view, localized mining disturbance is a favorable condition. In rock mechanics point of view, it presents a high degree of system stability in rock mass. Nevertheless, the migrated mining disturbance changes the degree of stability where it reaches, and may trigger breakouts where it travels. The traveling itself is the interplaying process between rock mass system and disturbances, it also generates new disturbances, likes a relay race, and so on. The paths paved by successive disturbances during their migration may turn into conduits for the coming disturbances, such that displacements are accumulated in the conduits, channels called in this research. Therefore, ruptures are most likely occurs along the channels, in the other word, to cluster onto the channels.

Globally, earthquakes are triggered by plate's movements which are driven by underneath mantle flow which is a continuous disturbance or energy input to the earth crustal plate system (Stein & Wysession, 2005). On the boundaries of the plates, have larger deformation, trap more strain energy with higher stresses, generate more disturbances, and prone to breakout.

Mining-induced seismicity is triggered by openings, stress release disturbances, which introduce energy flow from far ends to the openings. The energy flow increases the remnant rock mass strain energy, changes the strain energy composition (increasing deviatoric energy), and redistributes it unevenly, and more importantly interacts with locked-in shear zones on site.

Plate's movements provide displacement boundary conditions for the adjacent rock mass, people have no control on it, whereas mining openings provide stress boundary conditions, we have choices where and when to excavate, or to release stresses. Once we have a channel network representing the locked-in shear zones in a mine site, and a phenomenological model in it, it seems promising to provide a hazard evaluation to mine designs based on disturbances migration.

4 CHANNELIZED ROCK MASS MOVEMENT

4.1 *Certainty and uncertainty*

Rock mass motion is a deterministic physical process. Once the blocking geometrical configuration is determined, with certain initials and boundaries given, it is reasonable to predict rock mass states at any given time and space (stresses, strains and displacements) by Newton's motion law. This is the classical approach in science of mechanics. Conventional rock mechanical models all fit in this architecture, which, through undertaking faults/joints survey, realizes the blocks of rock mass, conducts the modeling. Nevertheless, in the history of science of mechanics, it is swarmed of scenarios that a beautiful theory is killed by a little ugly facts. Here, rock mass geometrical uncertainty and unknown unstable shear zones created by initial stress field, or lack of knowledge of them, destroyed the beautiful theory of mechanics. Nevertheless, it is different from micro scale Heisenberg uncertainty principle, the uncertainty in rock mass has two aspects, first, in the reality, there is indeed a definite geometrical configuration and initial stress conditions; second, human being has no ability to know them that exist in the reality. So that, although there is a unique solution in a rock mass motion at the given initial and boundary conditions, approximations are still dominated approaches in rock mass modeling.

The joints may keep developing and stress field may keep varying as proceeding mining excavations. Mining-induced seismicity spreads the traces of the movement, indicating locked-in shear zones spatially, and the time sequential seismicity details them in space and time, the more seismicity is recorded, the clearer traces are gotten, the clearer motion of rock mass converges to the solution of rock mass movement, so that CEM model will be a self learning system, by updating channel network geometry and its phenomenological behaviors.

4.2 *Translation and rotation*

In continuum mechanics, translations are governing and independent variables, whereas rotations are derived quantities from the translations. In the other word, rotation is not the freedom of the material movement. However, rock mass comprises of discontinuous grains and blocks, in this type of media rotations become the freedom of movements (Eringen, 1968). The rotations loosen the strengths of the rock mass. As Tarasov (2007) mentioned that fracturing, in deep underground, is formed by rotation of strips which are generated by an echelon of tensile cracks. Under high compression condition, shearing initiates rotation in the discrete block ensemble where rotation has less resistance than translation. When the rotation develops, the bearing stress against shearing partially disappears, the load is transferred over onto its vicinity along the shear trend, and so on, finally leads to shearing failures.

Even in a massive rock, when it experiences deformation, a displacement field is generated; the secondary field which is associated with displacement d is a rotation field ω, i.e. vorticity. During crack initiation, cracks coalescence brings into significant discontinuities, forming slices or strips inside rock mass, their buckling will lead to rotation with same direction of ω in the shear zone. Shear generates ω field, the ω field is enhanced by discrete rotations, shear zones becomes carriers for larger deformations/movements in depth underground. Figure 4-1 shows a fault propagates along a shear zone at a mine site.

Where ω is angular rotation, d is the displacement along the shear zone, τ is the shear stress.

In elastic micropolar theory (Eringen, 1968), the discontinuous grains in continuum material add in an anti symmetric rotation tensor and a moment stress tensor onto classical continuum theory. The moment stresses drives the grain rotating, measured by a rotation tensor. The destabilized area in the shear zone will have a smaller G, the shear stress drops as showed on Figure 4-2, as a result, the resistant moment drops, accelerated rotations lead to rolling, turns into a slip movement at a larger scale. As we know, the rolling movement has much less resistance than a slip, so that a shear failure consumes a large part of energy at cracking process, the following up rolling process goes very quickly due to less resistance (Brune, 2003; Tarasov, 2007). In underground seismic strain energy release is actually the energy release of cracking, rotation carries on the movement.

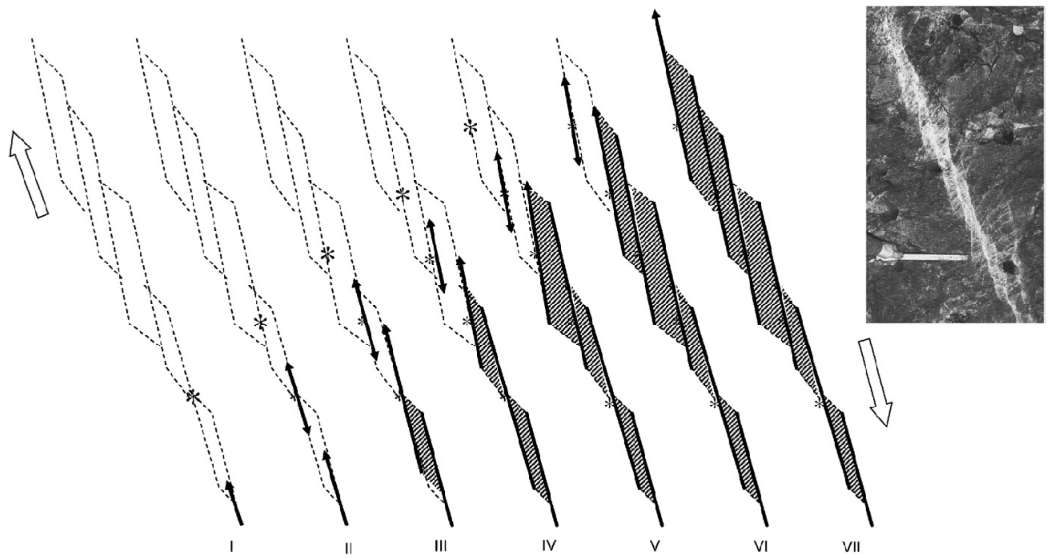

Figure 4-1 Cascade-like fault propagation due to advancing rupture triggering (Tarasov, 2008).

Figure 4-2 illustrates a simple shear deformation, once a zone in the domain is weakening, such as crack coalesce, the built-in rotation field is enhanced, leads to shear failure.

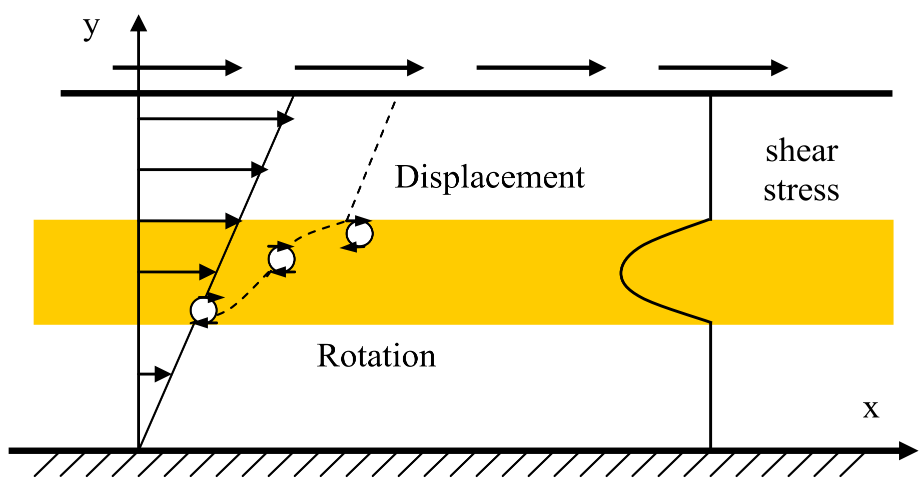

Figure 4-2 Rotation development at simple shear movement.

The govern equations for the simple shear:

$$\omega = \frac{1}{2}\frac{\partial u}{\partial y} \qquad \tau = G\frac{\partial u}{2\partial y} \qquad \rho\frac{\partial^2 \omega}{\partial t^2} = \frac{\partial^2 \tau}{\partial y^2} = G\frac{\partial^3 u}{\partial y^3} \tag{4-1}$$

In a triaxial test, micro cracks initiate and coalesce at somewhere in the sample, buckling and rotating releases the bearing stress, transfers over to its vicinity along the maximum shear direction with which they will cluster, until a massive shear damage occurs, shown in Figure 4-3.

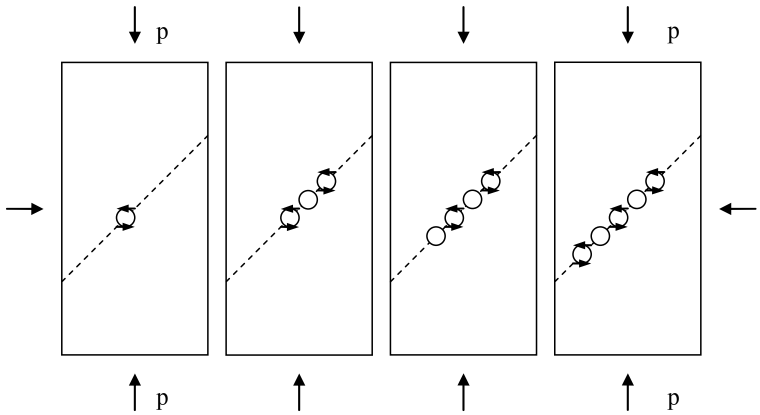

Figure 4-3 Fracturing and failure on triaxial test.

The rotation sequence tends to develop into spatial traces, along shear trends. The shear trends are locked-in stress states generated by tectonic movements, embedding in the large scale rock mass, and may be updated by mining activities. Shearing generates rotating, and rotating enhances shearing, they are mutually enhanced each other, distributing along shear trends, composing of channel element network, shown in Figure 4-4.

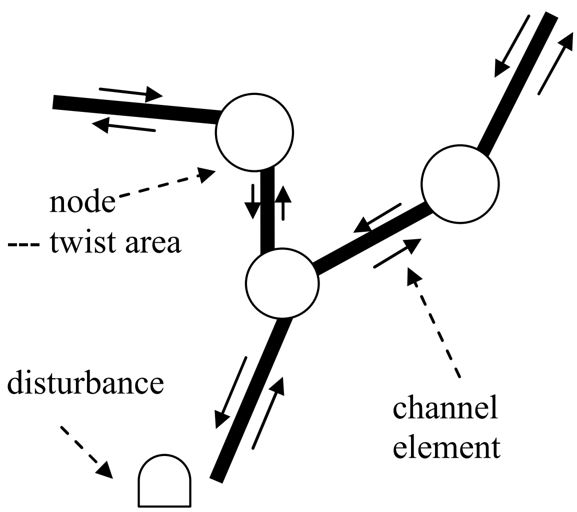

Figure 4-4 Channel network at mine wide scale.

The node is the joint area of channel elements, it accumulates the moment induced by jointed shearings, distributes the shearing movement among the element, once reaches a criterion, it ruptures and releases the holding moments to the jointed elements, a new disturbance comes into the network.

5 MODELING OF CHANNELS

Under ideal conditions, e.g. elastic continuum assumption, the movement induced by mine excavations is localized, seismicity should not escape the localized zone, but the nature of channel network at a mine site results in rock mass behavior that deviates from the expected elastic behavior allowing mining and seismic event disturbances to migrate remotely from the excavation site.

A Channel Element Model (CEM) is introduced in this research, to model mining induced disturbance migration in jointed rock media, to simulate chain-like rotational and slipping movement evolutions in shear zones. CEM is a mathematical method, with which to model rock mass time dependent, remote interaction processes from source disturbances, in contrast to mechanical contact interactions by DEM, or constitutive relations by FEM to model near source disturbance responses.

The elements in the model represent unstable shear zones embedded in the rock mass, along which translation and rotation may gear into a Domino so to propagate mining disturbances remotely under deep mining conditions. The spatial layout of the elements may appear as a network, which could be identified and updated by seismic event clusters.

The momentum equation of linear elastic continuum:

$$\rho\frac{\partial^2\vec{V}}{\partial t^2} = \mu(\nabla^2\vec{V}) + (\mu+\lambda)\nabla(\nabla\cdot\vec{V}) + \vec{F} \tag{5-1}$$

To curl the both sides of the equation, supposing volumetric force is constant.

$$\rho\frac{\partial^2\vec{\omega}}{\partial t^2} = \mu(\nabla^2\vec{\omega}) \tag{5-2}$$

$$\vec{\omega} = \frac{1}{2}\nabla\times\vec{V}$$

Equation (5-2) is a typical rotational wave governing equation, similar to shear wave.

Applying Green theorem to the right side of Equation (5-2)

$$\mu\int\nabla^2\vec{\omega}dv = \mu\int\frac{\partial\vec{\omega}}{\partial n}ds$$

It indicates a toque of a given element by its surrounding.

Discontinuities and their creation in rock mass reduce shear modulus and its associated resistant moment for rotating, at a meantime introduce additional resistance forces, trapping, damping and friction. If we consider the rotation propagation in a 2D zone shown Figure 4.1, with an initial rotational disturbance start at one end, the governing equation will be:

$$\rho\frac{\partial^2\omega}{\partial t^2} = G\frac{\partial^2\omega(x,t)}{\partial x^2} - G_r\omega - \eta_r\dot{\omega} - f_r N \tag{5-3}$$

Where G, G_r, η_r, f_r are equivalent coefficients of shear modulus, anti rotation coefficient, damping and friction. The total displacement will be measured by summing up rolling distances in the vertical section.

$$u(x,t) = \int\omega dy$$

A corresponding displacement equation could be (we are modeling the disturbances, gravity is canceled by the background vertical stress gradient, and the last item is dropped in the model:

$$\rho A\frac{\partial^2 u(x,t)}{\partial t^2} = AE\frac{\partial^2 u(x,t)}{\partial x^2} - AG_s(x)u - A\eta_s(x)\dot{u} - f_s(x)N + A\left.\left(\frac{\partial\sigma_z^0}{\partial z} - \rho g\right)\right|_z \tag{5-4}$$

Where E equivalent Young's modulus, G_s shear modulus, η_s damping force, f_s friction coefficient, A shear zone area.

$$\sigma(x,t) = E\frac{\partial u(x,t)}{\partial x}$$

Boundary conditions for a channel element:

$\sigma(0,t) = -P_1$ stress in an end node or tension (positive) on openings influence area.

$\sigma(L,t) = -P_2$ stress in an end node.

Initial conditions:

$u(x,0) = 0$, $u_t(x,0) = 0$

Equation 5-4 is a generalized form of shear zone disturbance migration governing equation. The actual shear slip composed of crack initiating into rock bridges as the first stage, rotating and rolling making the second and further cracking into smaller pieces, sliding in brecciated ensemble (rolling in smaller scale) as the third (Gehle & Kutter, 2003). Rotation is a gear that makes a disturbance migrates from one place to another along a channel element, a shear zone.

6 EXAMPLES

Figure 6-1 shows that at a mine site in 2.5 km depth, two areas A and B are 1km apart. They are connected by an unstable shear zone composed of strongly jointed rocks. A blast or new opening or a seismic event at area A introduced a disturbance, 50MPa stress drop. The disturbance attenuated over the distance it traveled, two and half an hour later, it reached area B at where it kept accumulating, and twisting area B, three and half an hour later since the disturbance was generated, an event was triggered at the area B. Simultaneously a new disturbance entered the zone and interacted with the previous disturbance.

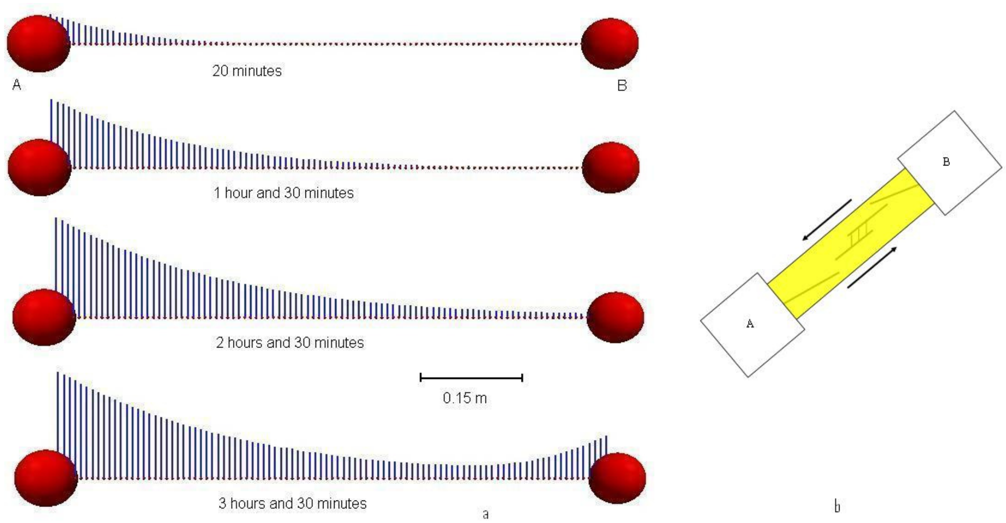

Figure 6-1 (a) disturbance and seismicity migration along a distance, (b) a generalized shear zone in rock mass.

Figure 6-2 shows a channel network, extending 1km in the longest dimension, which was identified with seismicity clustering. The links are unstable shear zones at a mine site, the nodes are intersection area of the links. A channel element model was built on it. As disturbances travel in the links between the nodes, the disturbances accumulate on nodes where they reach, so that the affected node is twisted, measured by moment. Once the moment exceeds the criterion on a node, a seismic event is triggered; and introduces new disturbances into the channel network. Here, the disturbance (a stress release) started at node A, triggered an event at B one hour later, then two disturbances interacted and migrated in the channel network, another event was generated at node C two hours later since the initial disturbance was introduced.

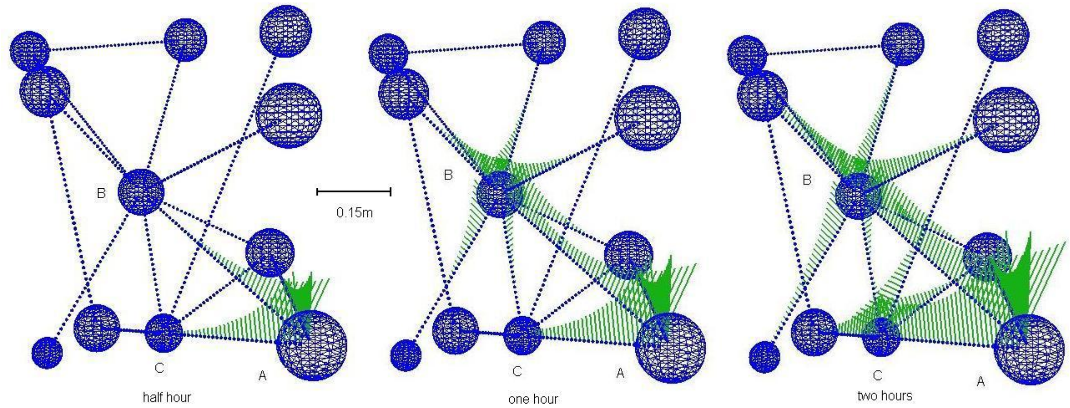

Figure 6-2 Disturbance and seismicity migration in a Channel Network.

7 CONCLUSION

Energy budget about mining excavation and seismicity makes a general rule to control excavation ratio during mining production. Excess energy rate is a guideline for the possibility of seismic failure at a mine site. However there is no way to apply them spatially and time dependently, to evaluate seismicity hazard in a space and time domain.

Locked-in shear zones on site set up a network (channel network), in which rotations of discontinuous ensemble enhance rock mass movements, and migrate mining-induced disturbances away from mining openings, triggering seismicity in the remote area.

Shear slip is a multi process composed of cracking, rotating, rolling and sliding, in which rotating is a gear to make the slip going.

The proposed Channel Element Model (CEM) presents an approach. Firstly, to identify lock-in marginal shear zones on mining site by seismicity clustering, the zones were exposed by seismicity induced by previous mining excavations historically. Secondly, to model disturbances (displacements by stress release) migrating in the channels with a phenomenological model.

The calibrated model could predict the displacement along the channels, with proper criteria of rupture in terms of displacement in channels and twisting moments on nodes, we could model seismicity migration induced by mining excavation.

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REFERENCES

Beck D. & Brady B. 2002. Evaluation and application of controlling parameters for seismic events in hard rock mines. *Int. J. Mech. Min. Sci.* 39: 633-642.

Beck D. et al. 1997. Induced stress and microseismicity in the 3000 orebody Mount Isa. *Getech. Geol. Engng*. 15:221-233.

Brady, B. H. G. & Brown E. T. 1993. *Rock Mechanics for Underground Mining*. ed. 2. London: Chapman & Hall; pp. 571-575.

Brune J.N. 2003. Precarious rock evidence for low near-source accelerations for trans-tensional strike-slip earthquakes. *Physics of the Earth and Planetary Interiors*; 137 p. 229–239.

Cook NGW. 1963. The seismic location of rockbursts. In: *Proceedings of the Fifth Rock Mechanics Symposium*. Oxford: Pergamon Press; p. 493-516.

Cook NGW. 1994. Why rock mechanics. *International Sot. for Rock Mechanics*. Lisboa Cedex; p. 975.
Cook NGW. et al. 1966. Rock Mechanics applied to the study of rockbursts. *J. S. Afr. Inst. Min*. Metall. 66:435-528.
Diederichs M.S. & Kaiser P.K. 2004. Damage initiation and propagation in hard rock during tunneling and influence of near-face stress rotation. *Int J Rock Mech and Min Sci*. 41:785-812.
Eringen A.C. 1968. Theory of micropolar elasticity. Liebowitz H., ed. *Fracture: An Advanced Treatise*. Academic Press; 2 pp. 621-729.
Freudental A. M. 1968. Statistical approach to brittle fracture. Liebowitz H. ed. *Fracture: An Advanced Treatise*. Academic Press; 2 pp. 591-619.
Gehle C. & Kutter H.K. 2003. Breakage and shear behaviour of intermittent rock joints. *Int J Rock Mech and Min Sci*. 40:687–700.
Glaser S. D. & Doolin D. M. 2000. New directions in rock mechanics -Report on a forum sponsored by the American Rock Mechanics Association. *Int J Rock Mech and Min Sci*. 37(4):683-698.
Goodman R. E. and Shi. G. H. 1985. *Block Theory and its Application to Rock engineering*: Prentice-Hall International Inc.; pp. 1-10.
Griffith A. A. 1920. *Phil. Trans. Roy. Soc*. London; Ser. A 221. pp. 163-198.
Irwin, G. R. Analysis of stresses and starins near the end of a crack. *J. Appl. Mech*. 1957; 24:361-364.
Kaiser P. K. et al. 2005. Seismic hazard assessment and mitigation. *NSERC Strategic proposal*. Geomechanics Research Centre, Laurentian University.
Kaiser P. K. and Diederichs M. S. et al. 2000. Underground Works In Hard Rock. *Tunneling and Mining Keynote Lecture at GeoEng2000*. Melbourne Austrilia; p. 88.
Kostrov B. V. and Das Shamita. 1988. *Principles of earthquake source mechanics*. Cambridge University Press.
Linkov A.M. 1994. Dynamic Phenomena in Mines and the Problem of Stability. *International Sot. for Rock Mechanics*. Lisboa Cedex; 3 p. 1799.
Linkov A.M. 1996. Rockbursts and the instabilty of Rock Masses. *Int J Rock Mech and Min Sci & Geomech. Abstr*. 33(7):727-732.
Linkov A.M. 2000. Instabilty, fracture acceleration and wave amplification. *Int J Rock Mech and Min Sci*. 37:31-37.
McGarr A. 2000. Energy budgets of mining-induced earthquakes and their interactions with nearby stopes. *Int J Rock Mech and Min Sci*. 37:437-443.
McKinnon S. D. 2006. Triggering of Seismicity Remote from Mining Excavations. *Rock Mech. Rock Engng.* 39 (3), 255-279.
Ortlepp W.D. 1997. *Rock fracture and rockbursts*. Johannesburg: South African Institute of Mining and metallurgy.
Ortlepp W.D. 2000. Observation of mining-induced faults in an intact rock mass at Depth. *Int J Rock Mech and Min Sci*. 37:423-436.
Ortlepp W.D. & Stacey T. R. 1998. Performance of Tunnel Support Under Large Deformation Static and Dynamic Loading. *Tunneling and Underground Space Technology*. 13(1):15-21.
Potvin Y. & Hudyma M. 2001. Seismic monotoring in highly mechanized hardrock mines in Canada and Austrilia. *The Fifith international symposium on rockburst and seismicity in mines*: South African Institute of Mining and Metallurgy; pp. 267-280.
Reid H. F. 1910. The Mechanics of Earthquake. the California Earthquake of April 18, 1906, *Report of State Investigation Commission. Washington D. C.*: Carnegie Institute of Washington; 2.
Salamon MDG. 1968. Two-dimensional treatment of problems arising from mining tabular deposits in isotropic or transversely isotropic ground . *Int J Rock Mech and Min Sci*. 5(2):159-185.
Scholz CH. 1990. The mechanics of earthquakes and faulting. Cambridge: Cambridge University Press.
Stein Seth & Wysession Michael. 2005. *An Introduction to Seismology, Earthquakes, and Earth Structure*: Blackwell Publishing; p. 11.
Tarasov B.G. 2007. Intersonic shear rupture mechanism. *Int J Rock Mech and Min Sci.* 45:914-928