3-Dimensional modeling of fault-slip rockbursting

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Abstract: A research program has been carried out at INERIS aiming to quantify rockburst potential from mining-induced fault-slip. As a part of the research, numerical modeling of fractured rock mass has been undertaken, using the three-dimensional distinct element code 3DEC. Results presented in this paper demonstrate a very good agreement between calculated deformations of modeled faults and the experienced rockburst sequence of the Estaque-sud district of the colliery.

1. INTRODUCTION AND GENERAL SETTING

At the Provence colliery, coal is mined at a depth reaching 1100 m. The seam thickness is around 3 meters, while strata dips westward around 10°. The longwall face method with caving process is used, involving high mechanization and self-advancing support for faces of 200 m of span. Rate of production has increased steadily all along the past, reaching now the value of 11 tonnes per shift and per day, with a average, daily rate advance of 6 meters per day and per working faces.

Nowadays, the coal mine experiences a daily average of 20 seismic events of magnitude 1.5 and greater, 15% of which are magnitude 2 and more. Most of these events are attributed to the goaffing process associated with the longwall mining operation. However, on an annual basis, many of these events result in serious rockbursting damages at the advancing face and along haulage gateways. As regards the southern part of the colliery and the mining of Estaque-sud district, which bêgan in 1987, many major tectonic faults have been suspected to play a major part in dynamic loading of the coal seam through fault-slip induced by mining.

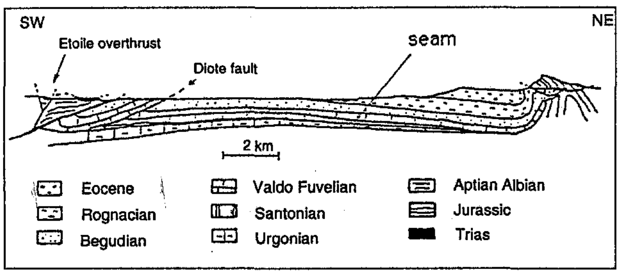

fig. 1- Geological cross-section of the basin

The general geological setting of the basin is quite simple. After Caviglio & al [1988], the structure is overridden by a major thrust sheet overthrusting northward, with a average dip of 25° (figure 1). Strike-slip, sub-vertical faulting is present all over the area, with lengths of several hundreds of meters. Two major zones have been distinguished in the coal field, with regard to the direction of the strata and stress measurements. In the zone we are concerned with, strong anisotropy of the principal stress components has been measured many times, characterized by high horizontal tectonic stresses and a sublithostatic vertical stress. Both have been explained by the regional, geological history (Piguet & Georges [1981], Revalor [1986], Gaviglio [1985]). Associated strata are made of limestones, qualified as hard and brittle (Josien [1981]).

2. ROCKBURST MECHANISMS AT THE ESTAQUE-SUD DISTRICT

For the last fifteen years, stimulated by the steady increase in the daily mine tremors and annually rockburst occurences, a research program has been undertaken at INERIS, aiming first to understand the mechanisms involved and then to improve prevention. Classified with regard to rockbursts locations and effects at the Provence coal mine, three main types of bursts have been recognized, as (Revalor [1988]) (figure 2):

- type 1: ends of the faces, especially on the old panel side. These bursts are now largely controled by means of destressing holes (figure 2a), although this method lacks of accuracy,
- type 2: coal bumps, buckling of the floor, more current at the present time, over length sometimes greater than a hundred meters, can affect the gateways either ahead of the face (old panel side) or behind the working face, at a distance ranging from 50 to 150 meters (figure 2b)
- type 3: strain bursts in unmined, overloaded stiff pillars (figure 2c)

Seimic energy associated with rockbursts varies around 10^8-10^9 Joules, with an associated Richter magnitude ranging from 2.2 to 3. At the Estaque-sud district of the mine (figures 5-6), mining started in 1987 with longwall T13. During the 3 years following period, with a span of one panel wide (200 m), then two (400 m) and three (600 m), 22 rockbursts[1] were recorded, starting with the mining of the second panel T14, most of the events being of type 2. A schematic description of the larger damages is suggested in figure 3, with following characteristics:

- violent expulsion of the coal in the gateway,
- no significant fracturation or convergence of the immediate hangingwall,
- quite often accompanied by floor heavage reaching 1 meter (whether due to buckling mechanism or deeper shear failure is still not clear (Mathieu [1989]). It is worthy noting that this kind of damage has been controlled for the last year by floor slotting ahead of the face, although the efficiency of this method has not been accurately estimated, due to the lack of data since its implementation.

1) We include here all significant dynamic events recorded, ranging from dynamic spalling to large, underground damages described here-after.

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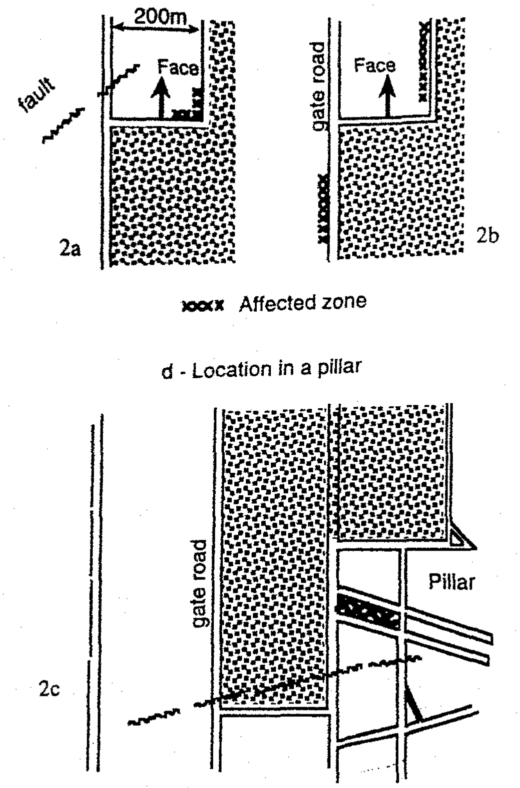

fig. 2- kinds of rockbursts

The main hypothesis for type 2 events tends to classify them more precisely as rockbursts triggered by dynamic loading generated by large mine tremors, induced by tectonic fault-slip or sudden failure of stiff bedding planes in the high roof. Naturally, potential means of confirming this kind of mechanism are very few because of the difficulties to get data. Extensions of the mining areas, poor access to faulted areas (one mined seam) and poor understanding of the roof behaviour do not permit to get valuable information. Two types of investigations have therefore been undertaken:

- developing a mine-scale seismic network, able to give location of each mine tremors with good accuracy as well as its energy and seismic moment. This should permit to relate the located focus of the mine tremor and the underground damaged areas and thus assert which mechanism of rupture may be considered. This has been undertaken two years ago (Ben Slimane & al [1990]). INERIS is currently improving the network to get accurate locations and better focus parameters,
- analysing with all avalaible data the major, suspected faults respectively with mining geometry and scenario to get a better understanding of potential fault-slip behaviour. This has been undertaken recently and use of numerical methods is presented in this paper.

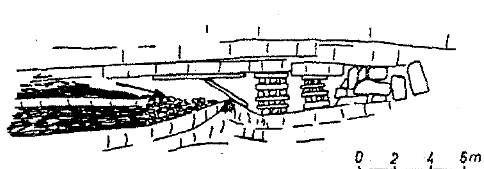

fig. 3- schematic description of the damages

3. NUMERICAL MODELING

Numerical modeling has been carried out aiming to quantify rockburst potential for the seismic triggering mechanism from fault-slip along major, pre-existing geologic structures. Because of both the mining configuration and orientation of the faults of the Estaque-sud area to be modeled, it was chosen to undertake three-dimensional numerical analysis. Eventually, the strongly discontinuous nature of the problem conducted us to the choice of the distinct element method.

Due to the lack of seismic data over the period of mining of the Estaque-sud district and the insitu conditions for mined areas of such extents, the aim of this study was to:

- examine the ability of the three dimensional distinct element method (3DEC, Itasca) to study fault-slip assessment for a complex system of discrete, deformable blocs,
- examine the fault-slip potential for large-scale faults lying in the mined area and correlate in space the modeled mining process and the incremental plastic deformations with the insitu recorded rockburst sequence,
- to bring forward a methodology of modeling closely associated with geological survey and above all with data from the newly settled seismic network available.

4. 3DEC SOFTWARE

3DEC is a PC-based computer program using the distinct element method and a central finite difference scheme to simulate the mechanical response of three-dimensional blocky systems. Handling either rigid or deformable blocs, the formulation used permits to simulate large displacements and rotations of the blocs relative to one another, including detection of new contacts, while the solution scheme is explicit in time. During each increment of time, Newton's law of motion is used to obtain velocities and displacements from the unbalanced forces. Mechanical calculations may be described as in figure 4, which shows the importance of the contact logic implemented. A complete description of this and of the calculation cycle are given by Cundall [1988] and Hart & al [1988] respectively. Note that when deformable blocs are used, modeled joints are sudivided in subcontacts corresponding to the finite difference tetrahedral zoning of the faces, while each surface node is the centroid of an area defined as the subcontact. This one keeps track of the interface forces as well as slipping or separation. Graphical interface is largely developed, permitting to model as efficiently as possible well-conditionned problems compared to their original complexity.

Modeling of rockburst mechanisms with 3DEC has been undertaken before, to simulate fault-slip behaviour of discontinuous medium, applied to fault and dyke slip at the Strathcona mine, Canada (Hart & al, [1988]), (Tinucci & al, [1990]). The numerical analyses were able to point out the consistency of fault-slip assessment in mine-induced seismicity and rockbursting.

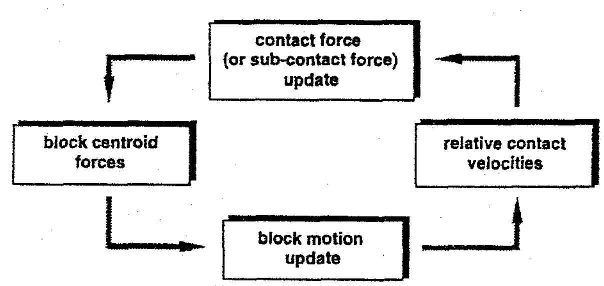

fig. 4 - 3DEC scheme calculations (after Hart, [1988])

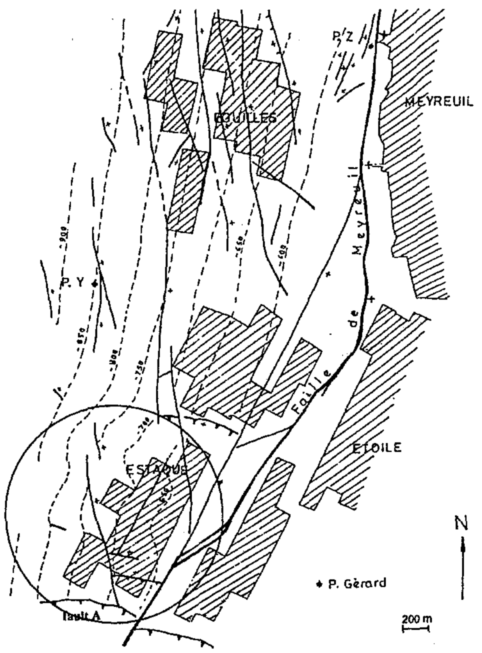

fig. 5 - map of the most recent mined districts

5. NUMERICAL PARAMETERS

Our 2800x1600x2400m model of the rock matrix consits of 188 convex blocks formed by 7 structural features, comprising 5 large-scale faults (500 to 2000 m of length, figures 5-6)) and two bedding planes (dipping east-west 10°) located at 150 m in the upper roof (representing coarsely the Fuvelian strata), and below the seam, and in the footwall respectively. Four longwalls (T13, T14, T25 and T15) are simulated, with a mining scenario reproducing the in-situ excavation process geometry. The four longwalls were then excavated in 15 incremental steps, made of deletion of blocs, (figure 6) with equilibrium reached at each step, providing a quasi-static analysis able to put forward the influence of the incremental mined areas on the plastic deformations along the modeled faults. Each step represents an excavated volume equivalent to two months of mining at a rate of 100 meters per month.

Deformable blocs, zoned by around 70.000 finite-difference zones, are assumed to behave elastically, while all structural features follow a perfect, elastoplastic behaviour, based on a Mohr-Coulomb yield condition (table 1).

table 1 - elasto-plastic parameters of the model

table 1	structural features	rock matrix MPa
stiffnesses	kn,ks=10000 MPa / m	K,G=13333,8000
M.C. parameters	Fric=35°, Coh= 0, Rt= 0 MPa	

table 2 - input stresses

table 2	σ1	σ2	σ3
value MPa	-40	-20	-17
dip °	120	30	0
dip dir. °	0	0	90

Initial pre-mining state of stress is chosen to be very close to available field measurements obtained in the Etoile-sud district, closest to the one modeled. Values and orientations are noted in table 2.

Two parameters are quantified in order to relate plastic deformation along each feature to each sequential excavation:

- $M = \sum_{SubC.} A_s D_\tau$ where A_S is the subcontact area and D_τ its tangential displacement. M may be interpreted coarsely as the seismic moment of the fault divided by its shear modulus. It characterizes the mechanical moment acting on the structure while new equilibrium is reached.
- $\Delta E = \frac{1}{2} \sum_{SubC.} F_s D_\tau$ where F_S is the tangential force acting at the subcontact location. ΔE is the non-recoverable, released energy dissipated by the excess shear force induced at each step.

These two parameters are related, in such a multi-step, quasi-static analysis by the relation: $M = \frac{\Delta E}{\tau}$ where τ is the tangential stress acting at the subcontact location.

6. RESULTS

Figures 7 and 8 indicate the energy dissipated through plastic strain and the parameter M at each step both with the rockburst sequence plotted on the right, vertical axis versus the step number of the simulation. Results show that only the simulated overthrusting fault (fault A) and upper bedding plane (feature I) show large plastic deformations. These deformations appear above all from starting of longwall 14 (mining step 8-9). Summing up briefly, we can do the following comments :

- the qualitative correlation between M for both strutures and rockburst sequence shows a good agreement
- rupture mechanism along fault A is due to shear failure, induced by both decrease in normal stress and increase in shear stress, coupled with stress tensor rotation. The amount

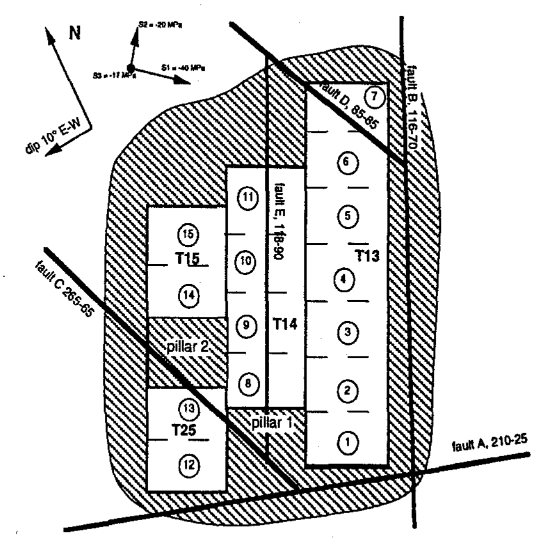

fig. 6 - modeling of the Estaque sud district faults are indicated with dip direction and dip

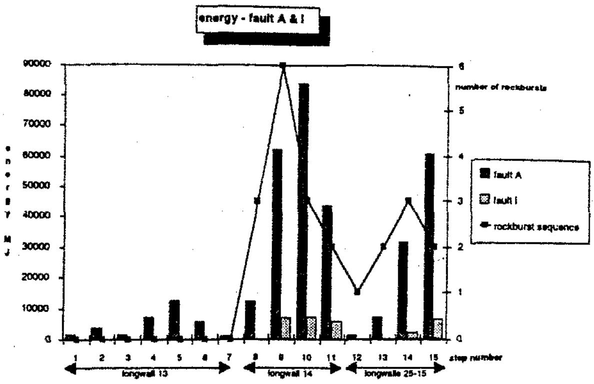

fig. 7 : energy dissipated at each step for joints A & I

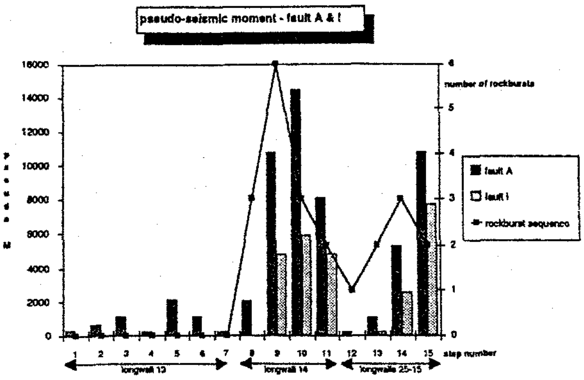

fig. 8 : parameter M at each step for structures A & I

of deformation seems essentially sensible to the width of the mined out area, i.e. extension from east to west. It decreases with extension in length of a longwall (steps 6-7-11). Geometric projections of locations of maximum shear displacement (figure 9) on the seam plane are approximately, vertically plumbed with the step excavation. Energy dissipated at step 9, if calculated on a daily basis, provides a value of 3.10^9J, which corresponds to an event with a order of magnitude of 3.

- failure mechanisms along bedding plane I are of two types: shear and tensile due to flexural behaviour. The relatively small energy dissipated is due to a low induced shear stress on the fault, parallel to the seam, and dipping 10° with regard to original principal stresses. In fact, tensile failure takes place essentially at steps 10, 11 and 15 with the widening of the mining area.
- Slip along fault A is essentially oblique, i.e. with a mixed offset of reverse and right-lateral strike faulting. This motion corresponds to the natural, thrust faulting of the structure. Interaction of the two structures A and I close to their intersection is difficult to estimate. It is worth noting that they most likely amplify each other because of the compatibility of the kinematics of the blocs.
- Along other features, there is no noticeable plastic deformation although induced stresses are unfavourable for most of them, i.e. ratio τ/σ increases, except significant deformation along fault C. However, if large strain was to be obtained on this modeled joint, it would conduct to reduce friction to unrealistic values (20-22°).

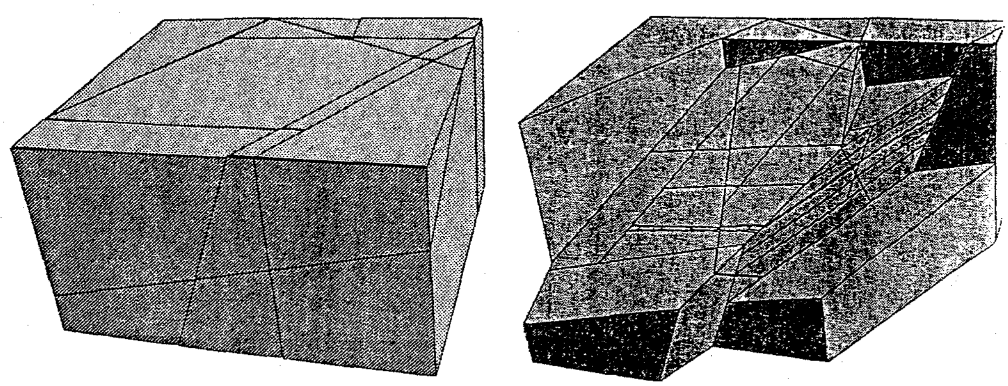

fig. 9a-b views of the rock matrix and the blocs

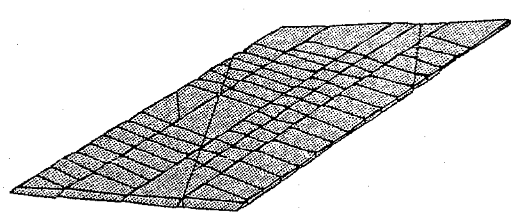

fig. 9c coal seam-longwall faces

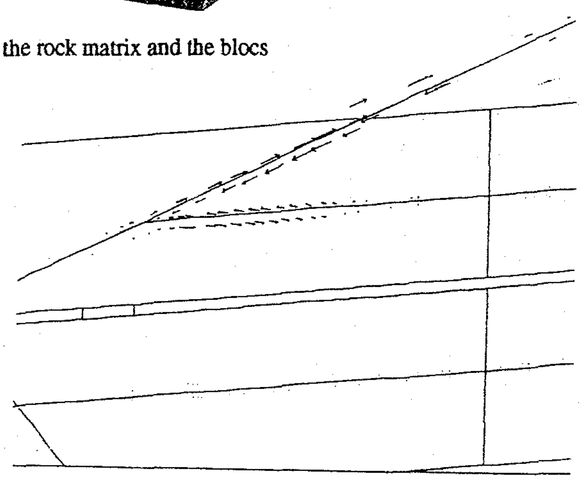

fig. 9d plastic shear displacement along discontinuities A & I
0.13 m after equilibrium along A

7. SUMMARY AND CONCLUSIONS

In fact, the aim of this study is to evaluate whether using modeling of typical, discontinuous problems in prediction of fault-slip rockbursting might be useful. This study shows an good agreement between the rockburst sequence and the response of some of the discontinuous features lying in the mined areas. Mechanisms involved in the response of the system are clearly identified, critical geometries and spans are pointed out, fault-rupture locations can be calculated, fundamental parameters as dissipated energy and seismic moment are estimated and seem realistic. The three-dimensional aspect in modeling is pointed out as very critical.

However, at the present time, no calibration can be demonstrated. As well, impact of failure along the structures on mining areas are impossible to estimate on a modeling point of view. Therefore, this methodology of three-dimensional modeling by the distinct element method appear as a method to be calibrated as closely as possible (figure 10):

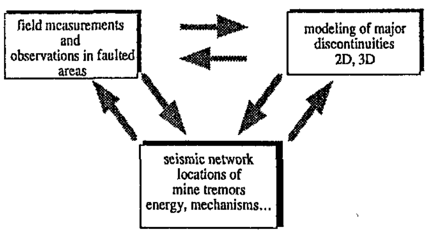

fig. 10 interacting fields to exchange data

- with insitu observations, i.e. detailed, geological survey of the faults and their characteristics, of the local disturbances of the coal seam, and others particular underground conditions.
- above all with seismic results from the settled network in 1991, giving presently locations and daily seismic energy distributions. Back analysis of selected tremors (location, energy, radiation pattern,...) compared with modeling could provide very interesting results. The seismic network is still undergoing improvements to locate more accurately, particularly in depth, and to gain understanding of the focal mechanisms involved in rockburst occurences. Association of seismic analysis and dynamic modeling is expected to come out as very promising.

In every case, this research directly benefits the mine by providing a method able to quantify numerous potential fault-slip problems, or qualify rockburst mechanism.

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