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Assessment of Susceptibility of Rock Bursting in Tunnelling in Hard Rocks

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ABSTRACT: The overburden of tunnels and underground caverns has been increasing in recent years. As a result, rock-bursting phenomenon has become probably one of the major concerns for the stability of such structures. This study is concerned with the assessment of susceptibility of rock bursting problem in tunnelling. The authors present a method for such a purpose by extending an earlier method developed by the authors for tunnels in squeezing rocks. This method is compared with other methods proposed for the predictions of rock bursting in underground excavations and it is applied to some tunnels where rockburst problems encountered to check its validity. And then its several applications to some tunnels with great overburden and under constructions are given and discussed.

1 INTRODUCTION

Squeezing and rock bursting problems in underground excavations are often encountered and they are major modes of failure in both short-term and long-term. Squeezing problem was investigated by the first author and his group in detail and a method for predicting the squeezing potential and deformation of tunnels was put forward and its validity was confirmed through applications to a number of tunnelling projects (Aydan et al. 1993, 1995, 1996). While squeezing problem is observed in weak rocks, rock-bursting problem is commonly seen in underground excavations in hard rocks. Rockburst could be particularly a very severe problem during the excavation as it involves detachment of rock fragments with high velocity. Mont Blanc tunnel in France, Gotthard tunnel in Switzerland, Dai-Shimizu tunnel and Kanetsu tunnel in Japan are some of the well known examples of rock bursting in tunnelling. Rockburst problems are also one of the common instability modes in deep mining in hard rocks and numerous examples are reported from South Africa and Canada (Bosman and Malan, 2000; Kaiser et al. 1993, 1996).

Several methods are proposed to assess the susceptibility of rock bursting in underground excavations. Ortlepp and Stacey (1994) recently present a detailed review of these methods. These methods can be broadly classified as energy methods, elastic-brittle plastic method, extensional strain method. Nevertheless, none of these methods is validated for assessing the susceptibility of rock bursting in tunnelling and its intensity. In this article, the authors presents a method for the assessment of susceptibility of rock bursting in tunnelling in hard rocks and this method is essentially a slight extension of their method proposed for tunnels in squeezing rocks. After presenting the fundamentals of the method, it is compared with other methods to check its merits and de-merits. Furthermore, its several application to a tunnel with great overburden and under construction is given and discussed.

2 ROCKBURST PHENOMENON

2.1 *Physical characteristics of Rock Bursting*

Rock bursting is generally associated with the violent failure of brittle hard rocks such as igneous rocks, gneiss, quartzite and siliceous sandstone. It is well known phenomenon of instability in mining for long time. When hard rocks are tested under uniaxial loading conditions, the fragments of rocks can be thrown to a considerable distance once the peak strength of rock is exceeded. The failure surface is mostly associated with an extensional straining. Rock bursting in underground excavations is quite similar to that under laboratory conditions. When rock bursting occurs in underground openings, rock fragments detach from surrounding rock and are thrown into opening in a violent manner like bombshells. The less severe form of rock bursting is observed as spalling.

2.2 Mechanical characteristics of rock bursting

It is known that rock bursting is said to occur in hard rocks having high deformation modulus while squeezing is observed in weak rocks having a uniaxial strength less than 20-25 MPa. Figure 1 shows typical stress-strain responses for both bursting and squeezing rocks. Bursting rocks are characterized with their high strength, higher deformation modulus and brittle post-peak behaviour. On the other hand, squeezing rocks are characterized with low strength, smaller deformation modulus and ductile post-peak behaviour.

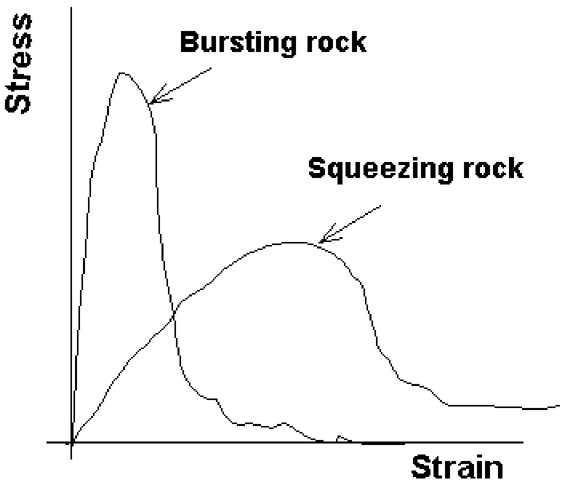

Figure 1 Typical stress-strain responses of squeezing and bursting rocks

The violent detachment of rock fragments during rock bursting is associated with how the stored mechanical energy is dissipated during the entire deformation process. As shown in Figure 2, if the intrinsic stress-strain response of rocks could not be achieved through its surrounding system in laboratory tests or underground openings, a certain part of stored mechanical energy would be transformed to kinetic energy. This kinetic energy results in the detachment of rock fragments, which may be thrown into the opening with a certain velocity depending upon the overall stiffness of the surrounding system and deformation characteristics of the bursting material (Jaeger and Cook, 1979). The first author observed this phenomenon even in granular crushed quartz samples confined in acrylic cells and dry initially sheared Fuji clay. It is observed that wrapping samples with highly deformable rubber-like strings greatly reduced the violent detachment of fragments even as seen in Figure 3. Although such materials could not delay or increase the overall confinement, they act as dampers to reduce the velocity and acceleration of detaching rock fragments, which may be one of very important observations in dealing with rockburst problem in underground excavations.

For rocks exhibit bursting phenomenon, the following identity must hold:

$$E_S = E_K + E_T + E_P + E_O \tag{1}$$

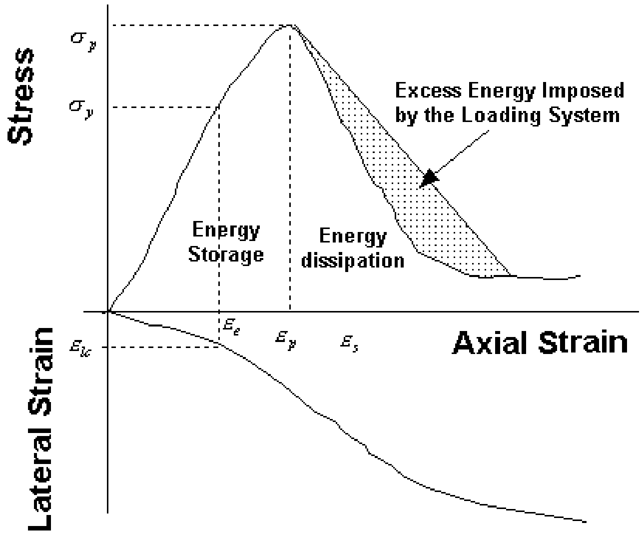

Figure 2 A simple illustration of the mechanical cause of rock bursting phenomenon

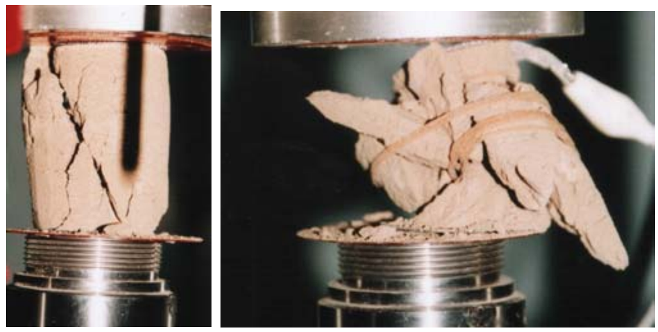

Figure 3 Post-failure views of dry initially sheared Fuji clay samples wrapped with rubber strings

Where E_S, E_K, E_T, E_P and E_O and stand for stored mechanical energy, kinetic energy, thermal energy, plastic work done and other energy forms, respectively. For a very simple case of one-dimensional loading of a block prone to bursting, one can easily derive the following equation for the velocity of the rock fragment if one assumes that the stored mechanical energy is totally transformed into kinetic energy (i.e. Arıoğlu et al. 1999, Kaiser et al. 1996):

$$v = \frac{\sigma_c}{\sqrt{\rho E}} \tag{2}$$

Where σ_c, ρ and E are uniaxial strength, density and elastic modulus of the detaching rock block. Furthermore, the maximum ejection distance d of the block for a given height h of the opening and horizontal ejection angle can be easily obtained from the physics as follows:

$$d = v\sqrt{\frac{h}{g}} \tag{3}$$

Where g is gravitational acceleration. Figure 4 shows the ejection velocity and throw distance of block as a function uniaxial strength of surrounding rock mass.

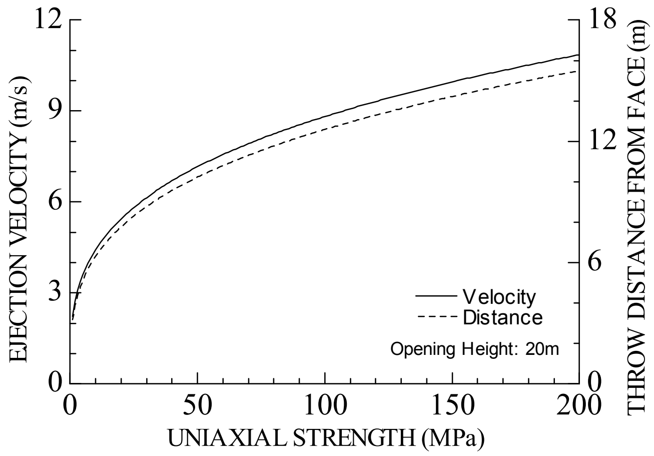

Figure 4 Ejection velocity and throw distance of rock fragment for an opening height of 20m as a function of uniaxial strength of surrounding rock

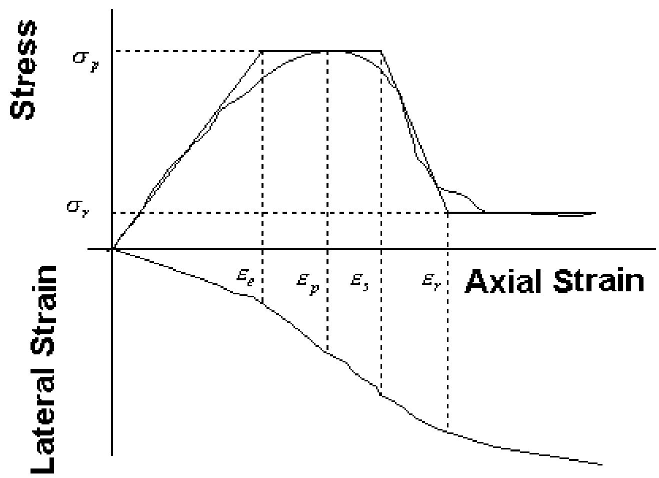

Figure 5 Illustration of strain limits for different states of rock under compressive tests

3 A METHOD FOR PREDICTING ROCK BURSTING AND ITS INTENSITY

Bosman & Malan (2000) recently reported that the overall behaviour of hard rocks could be very similar to that of squeezing rocks. The fundamental difference between squeezing and bursting is probably the strain levels associated with different states as illustrated in Figure 5. As noted from Figure 1, the strain levels for bursting rocks are much smaller than those for squeezing rocks. Figure 6 shows a plot of normalized strain levels by the elastic strain limit defined in Figure 5 for a uniaxial compressive strength range between 1 and 100 MPa. This figure is an extension of the earlier plot for squeezing rocks together with new data. The horizontal axis of the figure is the uniaxial strength of surrounding rock. It should be noted that we do not differentiate intact rock strength and rock mass strength on the basis of our own experiences and databases for rock masses and intact rocks. In other words, if the uniaxial strength values of intact rocks and rock masses are similar, their mechanical behaviour will be quite similar to each other.

The empirical relations shown in Figure 6 are those initially proposed for squeezing rocks by Aydan et al. (1993,1996) and they are also applicable to hard rocks with bursting potential. Furthermore, the empirical relations for other mechanical properties, which are required for analyses, can be applicable for rocks with bursting potential. For circular tunnels under hydrostatic initial stress state as shown in Figure 7, the strain levels and plastic zone radii can be obtained as follows (Aydan 1993, 1996):

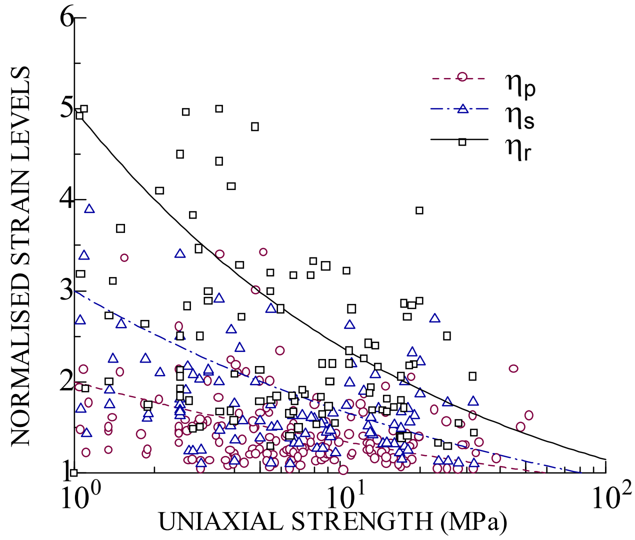

Figure 6 Comparison of normalized strain levels and empirical relations for squeezing and bursting rocks

Elastic state

$$\xi = \frac{\varepsilon_\theta^a}{\varepsilon_\theta^e} = 2\left(\frac{1-\beta}{\alpha}\right) \le 1 \quad (4)$$

Elastic perfectly plastic state

$$\xi = \frac{\varepsilon_\theta^a}{\varepsilon_\theta^e} = \left\{\frac{2\left[(q-1)+\alpha\right]}{(1+q)\left[(q-1)\beta+\alpha\right]}\right\}^{\frac{f+1}{q-1}} \quad (5)$$

$$\frac{R_p}{a} = \left\{\frac{2\left[(q-1)+\alpha\right]}{(1+q)\left[(q-1)\beta+\alpha\right]}\right\}^{\frac{1}{q-1}} \quad (6)$$

Elastic perfectly plastic – brittle plastic state

$$\xi = \frac{\varepsilon_\theta^a}{\varepsilon_\theta^e} = \eta_{sf}\left\{\frac{\frac{2\left[(q-1)+\alpha\right]}{(1+q)(q-1)}\left(\eta_{sf}\right)^{\frac{(1-q)}{f+1}} - \frac{\alpha}{q-1} + \frac{\alpha^*}{q^*-1}}{\beta + \frac{\alpha^*}{q^*-1}}\right\}^{\frac{f^*+1}{q^*-1}} \quad (7)$$

$$\frac{R_p}{a}=\left\{\frac{\frac{2[(q-1)+\alpha]}{(1+q)(q-1)}\left(\eta_{sf}\right)^{\frac{(1-q)}{f+1}}-\frac{\alpha}{q-1}+\frac{\alpha^*}{q^*-1}}{\beta+\frac{\alpha^*}{q^*-1}}\right\}^{\frac{1}{q^*-1}} \tag{8}$$

Where $\beta=\frac{p_i}{p_0}$; $\alpha=\frac{\sigma_c}{p_0}$; $\alpha^*=\frac{\sigma_c^*}{p_0}$; $q=\frac{1+\sin\phi}{1-\sin\phi}$; $q^*=\frac{1+\sin\phi^*}{1-\sin\phi^*}$

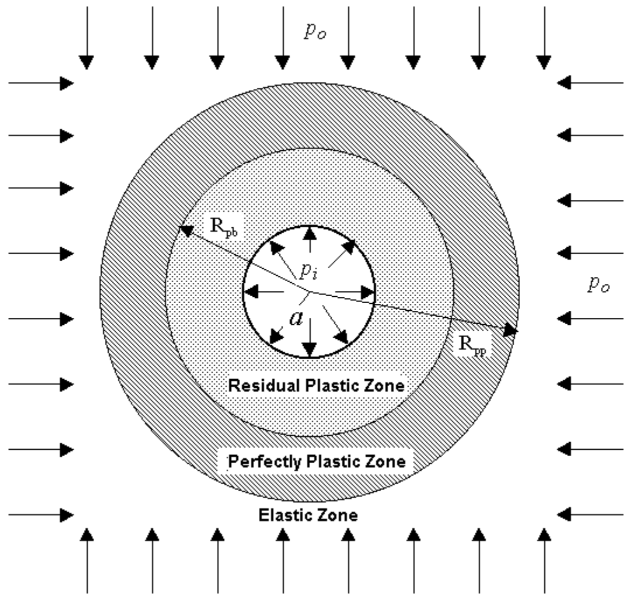

Figure 7 States around a circular tunnel and notations

The approach presented above can also be extended to situations, which involve complex excavation geometry and initial stress states. However, the use of numerical methods will be necessary under such circumstances as described by authors previously (Aydan et al. 1995).

4 COMPARISONS WITH OTHER METHODS AND APPLICATIONS

As mentioned in the introduction, energy methods, extensional strain method and elastic-brittle plastic method are used to assess the bursting susceptibility of hard rocks. These methods are briefly described herein and some equations are presented in order to make some comparisons with the method presented in the previous section.

4.1 *Energy Method*

Energy methods are used in mining for long time and it is based on the linear behaviour of materials. When the material behaviour becomes non-linear, it becomes difficult how to define the energy. The overstressed radius of rock around a circular tunnel under hydrostatic stress state can be obtained with the use of Mohr-Coulomb yield criterion and elastic stress components as:

$$\frac{R_p}{a}=\left\{\frac{[(q+1)(1-\beta)]}{[(q-1)+\alpha]}\right\}^{\frac{1}{2}} \tag{9}$$

The total energy per unit area in the overstressed zone is then obtained as follows:

$$w_{el}=\frac{1+\upsilon}{E}(p_o-p_i)^2 a\left[1-\left(\frac{a}{R_p}\right)^2\right] \tag{10}$$

Figure 8 shows the relation between overburden and elastic energy and radius of overstressed zone different uniaxial compressive strength of rock. The potential of bursting is quite high if the strength of rock is low. Kaiser et al (1996) suggested the following values for assessing the intensity of rock bursting on the basis of in-situ observations and the capacity of support members as given in Table 1.

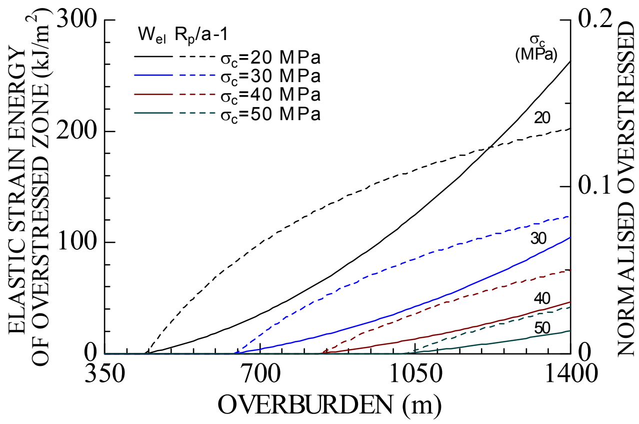

Figure 8 Relation between overburden and elastic energy and radius of overstressed zone

Table 1. Relation between energy and intensity of bursting

Intensity (KJ/m^2)	Energy (KJ/m^2)	Velocity (m/s)
Low	<5	<1.5
Moderate	5 - 10	1.5 - 3
High	10 - 25	3 - 5
Very high	25 - 50	5 - 8
Extreme	>50	>8

4.2 *Extensional Strain Method*

Stacey (1981) proposed the extensional strain method for assessing the stability of underground openings in hard rocks. He stated that it was possible to estimate the spalling of underground cavities in hard rocks through the use of his extensional strain criterion. The extensional strain is defined as the deviation of the least principal strain from linear behaviour. This definition actually corresponds to the definition of initial yielding in the theory of plasticity.

This initial yielding is generally observed, at the 40-60 percent of the deviatoric strength of materials. If this criterion is applied to circular tunnels under hydrostatic initial stress state, the radius, at which the extensional strain is exceeded, can be shown to be

$$\frac{R_p}{a} = \left(\frac{\left[\frac{1+\upsilon}{E} (p_o - p_i) \right]}{\varepsilon_c} \right)^{\frac{1}{2}} \tag{11}$$

Since

$$\varepsilon_c = \upsilon \varepsilon_e \text{ and } \sigma_c = E\varepsilon_e, \tag{12}$$

one can easily obtains the following:

$$\frac{R_p}{a} = \left(\frac{1+\upsilon}{E} \left(\frac{1-\beta}{\alpha} \right) \right)^{\frac{1}{2}} \tag{13}$$

4.3 *Elastic - Brittle Plastic Method*

In elastic-brittle plastic method, the strength of rock is reduced from the peak strength to its residual value abruptly. If this concept is applied to circular tunnels under hydrostatic initial stress state, the radius of plastic region can be obtained as follows:

$$\frac{R_p}{a} = \left\{ \frac{\frac{2-\alpha}{(1+q)} + \frac{\alpha^*}{q^*-1}}{\beta + \frac{\alpha^*}{q^*-1}} \right\}^{\frac{1}{(q^*-1)}} \tag{14}$$

4.4 *Comparisons*

The above methods are compared with the proposed method by considering a circular tunnel under hydrostatic initial stress state. The uniaxial strength of rock mass is assumed to be 20 MPa and the internal pressure was set to 0 MPa. The parameters required for analysis are obtained from empirical relations proposed by Aydan et al. (1993, 1996). In the computations, overburden is varied and the radius of plastic zone or overstressed zone is computed. Figure 9 compares the computed radius of plastic zone or overstressed zone. As expected from theoretical relation (13) of the extensional strain method, the overstressed zone must appear at shallower depths as compared with predictions of the other methods. The other three methods predict the yielding at the same depth. This difference is due to the value of yielding stress level associated with the extensional strain criterion. The radius of the plastic zone, estimated from the elastic-brittle plastic method, becomes quite large, and it even exceeds the one estimated from extensional strain method. The estimations from the proposed method and the energy method are quite close to each other. They are also more reasonable as compared with estimations from other methods.

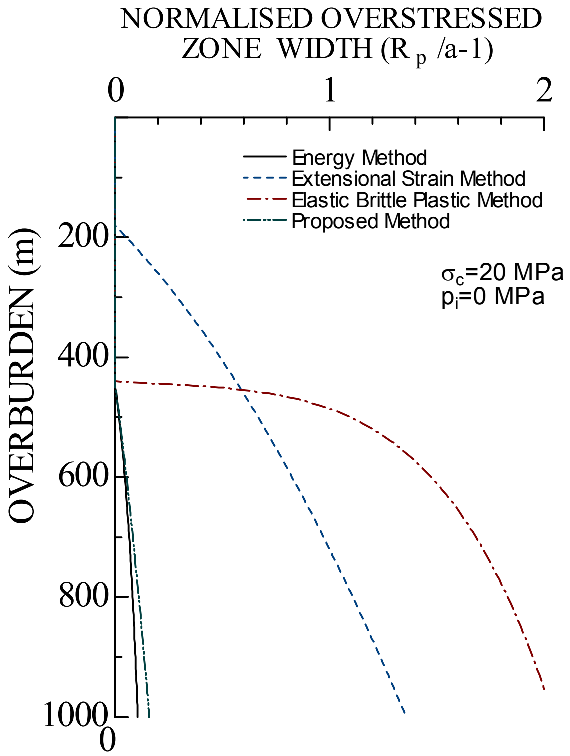

Figure 9 Variations of radius of plastic zone or overstressed zone with overburden, estimated from different methods

The proposed method is applied to a tunnelling project, which is now under construction. The tunnelling project is associated with an expressway construction and passes beneath high mountains in the Central Japan. Rock mass properties for this tunnel, which is 10km long and 12m in diameter, are estimated from the empirical relations developed for RMR classification by Aydan and Kawamoto (2000). Figure 10 shows the variations of overburden RMR and estimated level of bursting or squeezing and tunnel wall deformation along the tunnel alignement. Only the 600m long section of this tunnel excavated at the time of computations. The preliminary deformation measurements are quite close to the estimations shown in Figure 10.

The final application is concerned with the comparison of the deformation behaviour of a circular tunnel in bursting and squeezing rock mass. In the computations, the value of the competency factor (ratio of uniaxial compressive strength to initial stress) for both situations was chosen as 1. As expected from the behaviour of squeezing and bursting rocks shown in Figure 11, the tunnel wall strains becomes larger for tunnels in squeezing rock as compared with that in bursting rock mass. In addition, the radius of plastic zone in squeezing rock is larger than that in bursting rock.

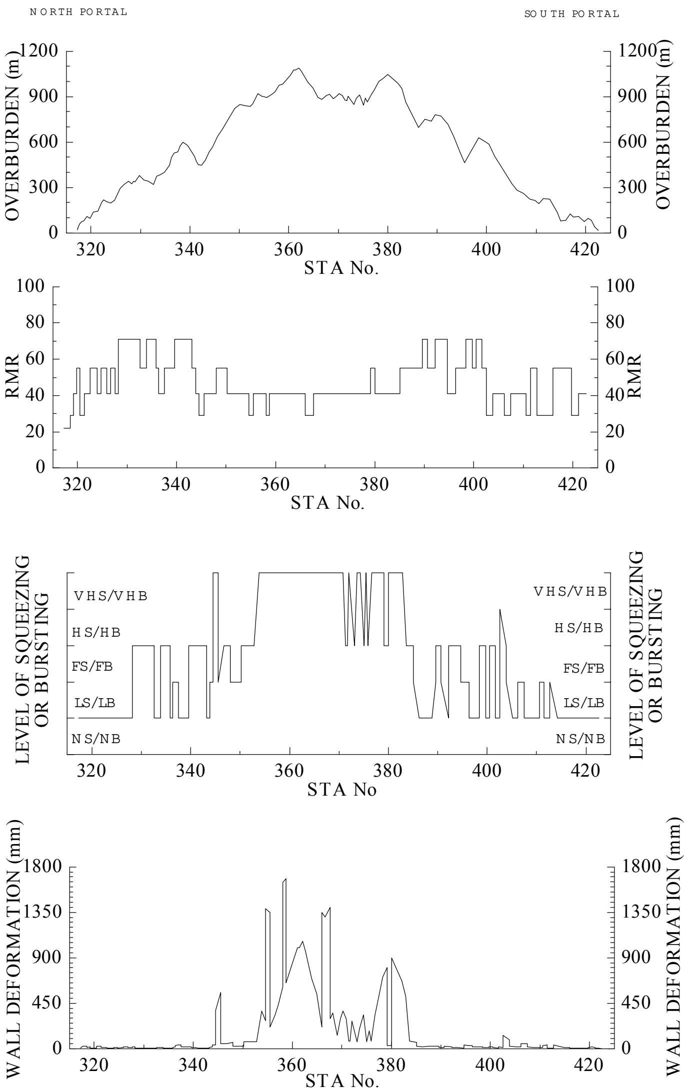

Figure 10 Predicted results for a 10km long expressway tunnel under constructions

5 CONCLUSIONS

The authors presented an extension of a method, which was initially proposed for tunnelling in squeezing rock, for tunnels in bursting hard rocks. It seems that many empirical relations proposed by the authors previously can also be used for rock prone to bursting with some confidence. Since the proposed method is capable of handling the mechanical behaviour of rocks prone to bursting, the estimations should be reasonable as compared with the elastic-brittle plastic model. Energy method yields similar results to those estimated from the proposed method. Although the proposed method is quite promising to predict the behaviour of tunnels under rock bursting conditions, it is felt that further studies are necessary. Especially the estimation of ejection velocity of rock fragments is quite important, as it is closely associated with the safety of workers during excavations.

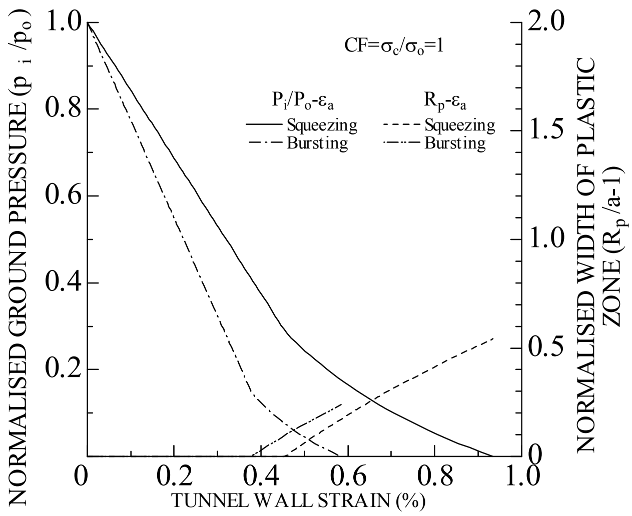

Figure 11 Comparison of computed tunnel wall strain and plastic zone of circular tunnels in squeezing rock and bursting rock.

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