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A new method for calculating energy release rate in tunnel excavation subjected to high in situ stress☆

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Summary Based on energy theory, energy release rate (*EER*) and local energy release rate (*LEER*), a new index called *FERR* (Fractional Energy Release Rate) is proposed, and this method can not only evaluate the risk of rock burst, but also can point out the location of high risk and the scale of rockburst. The *FERR* index is applied to the TBM assembling tunnel in Jinping Hydro Power Station II to evaluate the scale and intensity of rockburst, as well as the location where rockburst occurs. With FDM method adopted, the energy release rate of 3 excavation plans are calculated and the scale and risk of rockburst is evaluated, and the location of high risk of rockburst is also mapped. With *FERR* used in the evaluation, the rockburst is nicely controlled which ensured the safety and construction schedule of the project.

Introduction

When tunneling in high in situ stress areas, the energy embodied in the hard rock will be transferred inward the tunnel and released at the tunnel boundary, which makes the surrounding rock at high risk of failure and leads to rock fall, rockburst and even large collapse. In the excavation process, the energy release rage (*ERR*) is an important index to evaluate the stability of rock which has been verified by many researchers. Cook et al. (1966) put forward the *ERR* for the first time when studying the rock stability problem in gold mine in South Africa, and *EER* appeared as the average energy release rate. From then on, the *EER* index has been applied in lots of studies, such as Stecher and Fourney (1981), who employed the *ERR* index to study the propagation of a crack that is initiated and driven by an explosive and similar researches have also be conducted by Martel and Pollard (1989), Bazant and Kazemi (1990), Wang and Shrive (1994) and Zhou et al. (2010).

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Besides application to the mechanic research of rock specimen, the *ERR* have also been applied in evaluating the rock stability problems in mine and traffic tunnel. Xie and Feng (2001) studied the rockburst problem of a copper ore deposit, and optimized the support system based on the *ERR* index. Yan et al. (2001) used *ERR* index combined with response surface method in the rock stability evaluation in a nickel mine.

The *ERR* index is important to evaluate rockburst in deeply buried underground openings, Bagaraja et al. (2013) and Lu (2014). In addition, some researcher have developed new indexes based on *ERR*, such as Su et al. (2006) and Chen et al. (2008) who have developed local energy release rate (*LERR*) to evaluate the rockburst problems in zone with high in situ stress in hard rock and applied the *LERR* in some hydro power stations.

ERR and its derivatives are helpful in the estimation of rockburst in some situations, which have been verified by many studies. However, the location, intensity and scale of rockburst is not clear when the *ERR* and its derivatives are applied. In the present research, a new index called fractional energy release rate (*FERR*) is put forward, which overcomes the disadvantages of *ERR* and its derivatives. And the proposed *FERR* is applied in the determination of the risk, scale and intensity of rockburst in a TBM assembling tunnel in Jinping Hydro Power Station II.

Local energy release rate

Cook for the first time put forward the concept of energy release rate (*ERR*) in his rock burst research in South African gold mining. *ERR* means the energy per unit volume releases from the surrounding rock while certain volume rock is excavated in the tunnel excavation step. *ERR* is expressed by

$$ERR_i = \frac{W_i}{V_i} \tag{1}$$

where ERR_i is the energy release rate in excavation step i, and W_i is energy released from surrounding rock in excavation step i, and V_i is the rock total volume of excavation step i.

ERR is in fact average energy release rate of tunnel excavation step. However, the excavation of tunnel is a gradual process, the average *EER* is not suitable to evaluate the local energy released in each excavation step. Besides, rock is considered as elastic which is not suitable for damage analysis and stress redistribution induced by rock plastic failure.

To obtain the relationship between the energy release and the stability of local surrounding rock, the *LEER* is put forward. *LEER* is an index to describe the energy released from a certain element in each excavation step and given by:

$$LERR_{ji} = U_{ej}^{i-1} - U_{ej}^{i} \tag{2}$$

where $LERR_{ji}$ is the *EER* of element j from excavation step $i-1$ to i; U_{ej}^{i-1} and U_{ej}^{i} are the elastic strain energy stored in element j in step $i-1$ and step i, respectively. The elastic strain energy is defined as:

$$U_e = \frac{1}{2E}[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)] \tag{3}$$

where E is the elastic modulus of rock; σ_1, σ_2 and σ_3 are the principle stresses.

The *LEER* index can be used in the energy trace of a single element in the excavation process, in this way, the stress path of rock can be determined to locate the rock which is accumulating stress or releasing it. The relationship of *LEER* and *EER* can be expressed as:

$$ERR_i = \frac{\sum_{j=1}^{n} LERR_j \cdot V_j}{V_i} \tag{4}$$

where V_j is the rock volume of element j; V_i total rock volume of excavation step i, and n is total element number.

The local energy change of a single element can be traced by *LEER* index. However, *LEER* index is based on elastic assumption, and failure of rock cannot be considered. To overcome this shortage, a new index *FEER* (fractional energy release rate) is proposed, in which the rock failure can be considered.

The local energy release rate in the excavation process falls into the total interval

$$0 < LERR_i \le L_{\max} \tag{5}$$

where $L_{\max}$ is the maximum of *LEER*. The total interval can be divided into a series of small intervals as below, and each small interval represents a level of rockburst.

$$0 < LERR < l_1,\quad l_1 < LERR < l_2, \cdots, l_{i-1} < LERR < l_i, \cdots, \\ l_{n-1} < LERR < l_n = L_{\max} \tag{6}$$

where l_i is the characteristic value of interval, $i = 1, 2, \ldots, n$.

The total energy and volume of failed rock can be calculated in the numerical model, and the equation are given by

$$E_i = \sum_{j=1}^{m} LERR_j \cdot V_j, \quad V_i = \sum_{j=1}^{m} V_j \tag{7}$$

where E_i is the total release energy of failed rock in interval i; $LERR_j$ is the local energy release rate of broken element j; V_j is the volume of broken element j; V_i is the total volume of broken elements in statistic interval i, and m is the total broken elements of statistic interval i.

Then *FERR* is the total release energy of failed rock divided by total volume of certain interval, and it is defined as

$$FERR_i = \frac{E_i}{V_i}, \quad FV_i = V_i \tag{8}$$

where $FERR_i$ is the *FERR* of interval i, and FV_i is total volume of failed rock in interval i.

Practical use of the *FERR*

Jinping Hydropower Station II project as the Case study in Southwest China

The total capacity of this power station is 4800 MW with 8 hydroelectric generation units. Four water diversion tunnels about 16.67 × 4 km long, are excavated, two by drill