International Journal of Rock Mechanics and Mining Sciences 106 (2018) 74–83

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Analytical solution of energy redistribution in rectangular openings upon in-situ rock mass alteration

Xiangjian Dong, Ali Karrech*, Hakan Basarir, Mohamed Elchalakani, Chongchong Qi

School of Civil, Environmental and Mining Engineering, The University of Western Australia, 35 Stirling Hwy, Crawley WA 6009, Australia

ARTICLE INFO

Keywords:
Energy redistribution
Analytical solution
Rectangular opening
Complex analysis

ABSTRACT

This paper aims at deriving analytical expressions of mining-induced energy redistribution around rectangular openings that involve local alteration of rock mass properties. As energy combines the effects of strains and stresses simultaneously, this research work is intended to complement existing approaches that rely on stress-based stability criteria. The energy density on the boundaries and its distribution within the domain, obtained analytically through direct derivation, is compared to numerical solutions obtained by Finite Element simulation for a given hypothetical field case. The analytical and numerical solutions show a good agreement and reflect the importance of analytical solutions especially in the vicinity of severe geometrical singularities. Our parametric study shows that the initial stress coefficient and opening span-height ratio have great influence on the variation of strain energy density. We found that the energy density concentrates on the excavation corners and that the energy density concentration index value on the opening side boundary decreases when the span-height ratio decreases. Areas of energy reduction appear on the excavation boundaries, which transform from the top centers to the side centers as the initial stress coefficient increases. Our study indicates that both energy density concentration and reduction areas need to be considered in excavation design. The derived expressions of mining-induced energy redistribution can be considered as a tool to assess the stability of rock masses and predict failure conditions such as rock burst and mine seismicity around non-circular shaped openings.

1. Introduction

The concept of thermodynamic potentials balance has become instrumental in complex resource engineering modelling.[1] In particular, the transfer of energy due to rock materials weakening has attracted a considerable research interest.[2,3] The energy redistribution due to mass alteration through anthropogenic activities has been attracting a considerable interest, especially to assess rock burst and seismicity.[4–12] Recent theoretical studies, numerical simulations, laboratory tests and in situ measurements indicate that energy changes due to excavation is a major cause of underground resource/construction engineering disasters.[13–20]

As indicated in Table 1 there are essentially four approaches to studying the energy evolution due to excavation. Apart from field work which, researchers used integral formulations, numerical approaches and local analysis to investigate the impact of rock alteration on energy exchanges. As a pioneer of integral formulation, Cook[21] showed that in elastic mediums the transferred elastic strain energy into the surrounding rock strata after excavation equals half of the total energy loss. Walsh[22] used integral formulation to propose a general calculation method to evaluate each energy component due to underground arbitrary opening excavation. In a later integral formulation study, Salamon[23] further investigated the general expression of energy and how it changes in tabular excavation by assuming a slit model. Similarly, Napier[24] used a unified method to calculate the integral form of energy changes after excavation by considering multiple discontinuities within rock strata. More recently, Jaworski[25,26] used integral formulation and applied elastic energy distribution as an index to evaluate the sesimicity level.

Mitri et al.[6] proposed a simple finite element approach to calculate the mining-induced energy storage rate and estimate strain burst potential. The particularity of their approach is that it combines the integral formulation with numerical analysis. Other researchers[27,28] combined field work with numerical approaches to investigate the energy redistributions in circular openings. In particular, the work of Jiang et al.[27] predicts the intensity of a rock burst within deep tunnel excavation. Their results indicate that the rock burst is highly related to the local energy release rate.

* Corresponding author.
E-mail addresses: xiangjian.dong@research.uwa.edu.au (X. Dong), ali.karrech@uwa.edu.au (A. Karrech), hakan.basarir@uwa.edu.au (H. Basarir), mohamed.elchalakani@uwa.edu.au (M. Elchalakani), chongchong.qi@research.uwa.edu.au (C. Qi).

https://doi.org/10.1016/j.ijrmms.2018.04.014
Received 26 October 2017; Received in revised form 12 January 2018; Accepted 7 April 2018
1365-1609/ © 2018 Published by Elsevier Ltd.

Table 1
Literature summary of energy evolution during excavation.

	Shape	Method		
		Local analysis	Integral format	Num.
Cook[21]	Rectangular		✓	
Walsh[22]	Arbitrary		✓	
Salamon[23]	Arbitrary		✓	
Napier[24]	Rectangular		✓	
Mitri et al.[6]	Arbitrary		✓	✓
Jaworski[26]	Arbitrary		✓	
Jiang et al.[27]	Circular			✓
Li et al.[28]	Circular			✓
Fan et al.[20,29]	Circular	✓		
He et al.[10]	Circular	✓		✓
Wang et al.[11]	Beam	✓		
Bnaka et al.[13]	Rectangular	✓		

Local analysis of energy redistribution is a new research area that is attracting an increasing interest especially by the tunnelling scientific and engineering community, which explains why most of the contributions focus on circular openings. For instance, Fan et al.[20,29] derived local expressions of strain energy with different unloading conditions and various tunnelling methods to evaluate the strain burst potential. In addition, He et al.[10] quantitatively calculated the elastic strain energy before and after tunnelling. Moreover, Wang et al.[11] obtained the local energy expression but they considered the overburden of the working face as a cantilevered beam and assumed that the stress in a coal pillar increases linearly with distance. These studies offer a foundation for advanced case studies where energy budgets are important to quantify.

Banka et al.[13] found a qualitative relationship between the calculated energy changes and the induced seismicity by comparing field measurement data with analytical solutions. They developed a regression model and applied it in Polish coal mining area; a relatively accurate reconstruction of the changes in tremor energy density was observed. The work of Banka et al.[13] is the only contribution that uses local analysis to describe the energy distribution around rectangular openings. Their semi-analytical approach uses a boundary value method which involves infinite integrals (Laplace equations). To solve the infinite integral and obtain the stress and strain distribution, Banka et al.[13] used Jaworski's method which is commonly used to approximate Laplace transforms.

In this paper, we propose a novel approach to solve the problem of energy redistribution around a rectangular opening. Unlike existing approaches that use integral formulation,[21–26] numerical approaches,[6,27,28,10] or local analysis that is restricted to circular shapes,[20,29,10] we use local analysis technique that does not require infinite integral approximation since it relies on conforming mapping and complex theory. We test the new approach on rectangular openings in this paper, but the proposed technique can be generalised to arbitrary shapes. The rectangular shape has been selected because it is common in underground constructions (such as longwall roadways, stopes and chambers). To ensure that the proposed solution method is accurate and reliable, we used the finite element method to verify it. By comparing the outcomes of both approaches, we highlight the advantage of analytical solutions in the vicinity of singularities such as corners. Based on the derived analytical solution, we analyse the influence of excavation on the change of energy within the considered domain. To draw general conclusions that can apply to various mining contexts, we conduct a parametric study by examining the evolution of strain energy density under different in situ stress conditions and opening parameters. Hence, the proposed study is meant to be comprehensive and applicable to design rectangular opening that obey the plane strain kinematic conditions.

2. Energy expressions in analysed domain

Underground excavation can be perceived as a stress relaxation process that is compensated by a stress concentration at the boundaries, while some of the energy is stored in the surrounding rock. When the stress concentration reaches the rock's strength, rock failure occurs; the stored energy sudden release can cause abrupt responses within the rock mass.[30–32] Therefore, inspecting the energy changes in regional rock masses due to excavation is important. To obtain the magnitude of such strain energy accumulation before and after excavation, we assume that the hard rock is in the linear elastic regime. The accumulated strain energy can be expressed as follows:

$$U_{A,A'} = \int_{V_A, V_{A'}} w dV \tag{1}$$

where A and A' represent the mined-out and remaining domain of rock strata, respectively, $w = \frac{1}{2}\sigma_{ij}\varepsilon_{ij}$ is energy density where the convention of repeated indices is used, σ_{ij} is Cauchy's stress and ε_{ij} is the deformation. In 3D isotropic homogeneous materials, the strains can be related to the stresses by Hooke's law which reads $\varepsilon_{ij} = ((1+\nu)\sigma_{ij} - \nu\sigma_{kk}\delta_{ij})/E$, where E is Young's modulus, ν is Poisson's ratio, and δ_{ij} is Kronecker's symbol. Hence, the strain energy density can be written as:

$$w = \frac{1}{2E}[(\sigma_x^2 + \sigma_y^2 + \sigma_z^2) - 2\nu(\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_x) + 2(1+\nu)(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)] \tag{2}$$

Based on Eq. (2), we quantitatively calculate the distribution energy per unit volume before and after deep rectangular excavation. We also use the integral Eq. (1) to obtain an overall energy description within the mined out and remaining domains.

2.1. Initial energy in analysed domain

To derive the energy expressions before and after excavation, some important assumptions can be made. First of all, the excavation is long enough to consider that plane strain conditions apply in any cross-section. We also assume that the rectangular excavation is initially subjected to a far field compression stress field σ_x^p and σ_y^p, where the superscript “p” refers to “primitive”. In the coming sections, we also use “m” as a superscript to refer to “post-excavation” variables. It is also assumed that the opening axes are aligned to the principal stress field directions. The surrounding rock is continuous, homogeneous, isotropic and linear elastic.

Fig. 1 illustrates the geometry of the model and explains the orientations of the different stress components. In the plane strain conditions (Fig. 1b), the strain component parallel to the opening is given by: $\varepsilon_z = \frac{1}{E}[\sigma_z - \nu(\sigma_x + \sigma_y)] = 0$, which corresponds to a stress: $\sigma_z = \nu(\sigma_x + \sigma_y)$. Substituting these strain and stress components into Hooke's law, we obtain the constitutive equation in plane strain condition:

$$\begin{cases} \varepsilon_x = \dfrac{1}{E}[(1-\nu^2)\sigma_x - \nu(1+\nu)\sigma_y] \\ \varepsilon_y = \dfrac{1}{E}[(1-\nu^2)\sigma_y - \nu(1+\nu)\sigma_x] \\ \gamma_{xy} = \dfrac{2(1+\nu)}{E}\tau_{xy} \end{cases} \tag{3}$$

Hence, the 2-D strain energy density function is given by:

$$\begin{aligned} w &= \frac{1}{2}(\sigma_x\varepsilon_x + \sigma_y\varepsilon_y + \tau_{xy}\gamma_{xy}) \\ &= \frac{1+\nu}{2E}[(1-\nu)(\sigma_x+\sigma_y)^2 - 2\sigma_x\sigma_y + 2\tau_{xy}^2] \end{aligned} \tag{4}$$

Knowing that before excavation the compression stresses, σ_x^p and σ_y^p, are principle stresses, the shear stress in the cross-section plane is zero ($\tau_{xy}^p = 0$). Therefore, the strain energy in the analysed domain before

Download English Version:

https://daneshyari.com/en/article/7206179

Download Persian Version:

https://daneshyari.com/article/7206179

Daneshyari.com