JME

Journal of Mining & Environment,
Vol. 9, No. 4, 2018, 999-1008.
DOI: 10.22044/jme.2018.7014.1543

Simulating energy method for grout-induced crack analysis of rock structures at Chadormalu mine by extended finite element method

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Received 25 April 2018; received in revised form 28 July 2018; accepted 28 July 2018
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Abstract
Fracture mechanics is a vital component involved in studying the exact behavior of rock materials. Detection and assessment of the behavior of rock joints injected by grout plays an important role in numerical modelling in rock mechanic projects. The importance of mechanisms associated with initiation and propagation of cracks due to hydraulic fracturing has led to a considerable interest in investigation and analysis of this phenomenon. In this work, the process of propagation of cracks on the wall of boreholes, drilled in single and bi-material structures, was simulated in ABAQUS software employing the extended finite element method. The energy method was implemented to obtain the stress intensity factor and energy release rate through applying J integral around the crack tip. The method was applied to two rock types, diorite and granite at the Chadormalu iron mine located in the central part of Iran. It was concluded that assuming the same geometry, the possibility of crack propagation at the boundary between two materials was more than the single material medium. Therefore, in dealing with a bi-material medium, if the purpose is to measure the *in situ* stresses, the measurement should not be performed on the boundary between the two materials.

Keywords: *Fracture Mechanics, Bi-Material, Energy Methods, Extended Finite Element Method.*

1. Introduction

The application of rock mechanics and geotechnical concepts in mining engineering plays a dominant role, especially in the slope design of open-pit mines, in the stability analysis and support design of underground openings as well as *in situ* stress measurements [1-3]. In general, there exist three main approaches for such an analysis: analytical, numerical, and empirical. The analytical methods have achieved an extensive reputation among researchers for predicting highly accurate stress and strain field around openings [4-6]. However, in terms of fracture mechanism, there still exist deficiencies owing to the complexity of the geometry of cracks combined with the complicated constitutive behavior for rock materials. To this aim, in parallel to numerical modeling, the use of physical modeling has obtained an international acceptance [7]. Especially, by development of geotechnical centrifuge machine in solving the problem of scale effect, the results of physical modeling are more reliable [8-10]. However, due to the complexity of the failure mechanism in heterogeneous and anisotropic media, numerical modeling is still more applicable than physical modeling for those media [11, 12].

Discontinuities and fractures are the natural structural drawbacks of rocks that exist at different scales (several millimeters to several thousands of meters) and determine the behavior of rock masses. The large-scale behavior of the fracture process in rocks is widely affected by the behavior of micro-cracks. Therefore, the initiation and propagation mechanisms of the cracks among the rocks are diverse in different conditions. Therefore, the necessity of knowledge on the mechanism of initiation and propagation of the hydraulic cracks in various engineering fields has led to a great interest on the analysis of this phenomenon, and the attempt to achieve an appropriate model for its simulation. However, the significance of the hydraulic fracturing process in the oil and gas industries in order to achieve hydrocarbon reserves or increase their production rate and the land improvement has been the main motivation to develop such models [13].

The essential step in establishing a relation between the specimen failure stress and crack dimensions was taken by Griffith in the early 20th century. In a study published in 1920, Griffith used the stress analysis method around an elliptical hole, which was carried out seven years earlier by Inglis to solve the propagation of an unstable crack [14]. With the application of the first law of thermodynamics, Griffith could establish the theory of failure based on simple energy equilibrium [15].

In 1956, Irwin presented the concept of the strain energy release rate (SERR) for metals, which was a generalization of the Griffith's theory [16]. Simultaneously, Irwin et al. noticed an article published by Westergard in 1939 [17]. In this paper, a method was presented for stress and displacement near the tip of the crack using a theory based on the complex numbers. Using this method, Irwin showed that stress and deformation near the tip of the crack could be described using a specific coefficient; the coefficient had a direct relation with SERR. This parameter was later known as the stress intensity factor (SIF). In the same years, Williams also described another method based on the Airy stress function to specify the stress and displacement around the tip of the cracks [18]. Both methods proposed by Westergard [17] and Williams [18] led to similar results for elastic stresses around the tip of the cracks.

The milestone of the research achievements in the field of fracture mechanics could be considered around 1960s. By this period, the linear elastic fracture mechanics (LEFM) principles had been well known. Subsequently, most research works focused on the assessment of crack tip plasticity. When significant plastic deformation occurs at the tip of the crack, the assumptions made in the linear elastic fracture mechanics will not be valid any more. In the short period of 1960-61, several researchers were working on modifications on the relations for use in elastoplastic stress analyses around the tip of the cracks [13].

Irwin presented the plastic area correction model using LEFM [16]. Dugdale [19] and Barenblatt [20] both developed more realistic models based on the narrow strip of the yielded material at the tip of the crack. Wales proposed another failure criterion based on the crack tip opening displacement (CTOD) [21]. In 1968, Rice succeeded in generalizing the concept of SERR for materials with elastoplastic behaviors [22]. He showed that the non-linear SERR could be calculated using the line integral of J in an arbitrary path around the crack. Hutchinson related the integrals J of the materials with the non-linear behavior to the stress field at the tip of the crack [23]. These analyses indicated that J could be considered as a non-linear SIF and also an SERR. In 1980, Shieh et al. [24] provided a theoretical framework for applying the science of fracture mechanics in design. Based on this framework, the mathematical relation between toughness, stress, and dimensions of the crack was determined based on the J integral. Furthermore, by establishing a relation between J and CTOD, they showed that each one of these two characteristics could be taken into account as a parameter for estimating the failure of structures [24]. The development of fracture mechanics in the years following 1980 further focused on the materials with non-linear time-dependent failure behaviors like viscoelasticity and viscoplasticity. Moreover, the effects of the other coefficient called T-stress on crack behavior were widely considered by the researchers.

Owing to the complexity of the geometry of fracture problems, along with diverse constitutive models for materials, numerical analysis was employed in fracture mechanics as well [11, 12]. Different numerical methods were used to determine stress and displacement fields around discontinuities [25-31]. One of the most efficient numerical approaches was devoted to the extended finite element method, which enabled modeling singularities around crack tips, material interfaces, and voids through adopting appropriate base functions [32-34].

Herein, a piece of XFEM code was implemented through the ABAQUS software in order to model crack propagation along a bi-material interface. Initially, the code was validated by applying to a single crack, and comparing with existing analytical solutions in both the one material and bi-material media. Subsequently, crack propagation along a bi-material interface at the wall of a horizontal grouting borehole was investigated.

2. Theoretical background

The concept of stress intensity factor (SIF) was defined by Irwin (1956) as follows [16]:

$$\begin{Bmatrix} k_I \\ k_{II} \\ k_{III} \end{Bmatrix} = \lim_{r\to 0,\theta=0} \sqrt{2\pi r} \begin{Bmatrix} \sigma_{22} \\ \sigma_{12} \\ \sigma_{23} \end{Bmatrix} \quad (1)$$

where r is the radial distance from the crack tip, σ_{ij} is the stress around the crack, and k_i is attributed to 3 types of independent kinematic displacements associated with the upper and lower surfaces of the crack tip.

The problem of a crack on the wall of a borehole in a continuous isotropic medium is illustrated in Figure 1. As discussed in Saouma [13], a comprehensive review of fracture mechanics, the above problem is suggested to be solved under two different conditions. In the first case, the length of the crack is negligible compared with the diameter of the borehole, while in the second case, it is assumed very large compared with the diameter of the borehole.

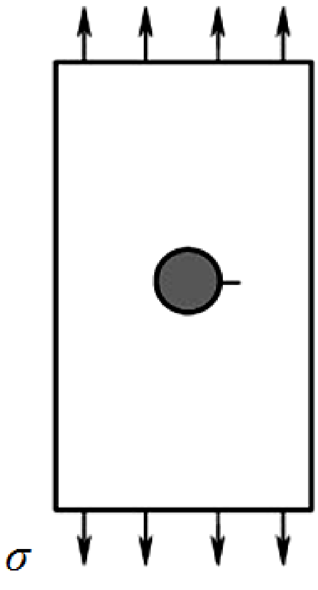


Figure 1. A crack on the wall of a borehole in a continuous isotropic medium [13].

In these two cases,

$$a/D \downarrow \longrightarrow \mathrm{K}_I = 3.36\sigma\sqrt{\pi a} \quad (2)$$

$$a/D \uparrow \longrightarrow \mathrm{K}_I = \sigma\sqrt{\pi\left(\frac{2a+D}{2}\right)} = \sqrt{1+\frac{D}{2a}}\sigma\sqrt{\pi a} \quad (3)$$

where a is the crack length, D is the diameter of the borehole, σ is the intensity of the tensile stress, and K_I indicates the SIF for the opening mode of crack.

The problem of a midline crack in a bi-material continuous medium, illustrated in Figure 2, has been investigated by some researchers theoretically [35-36]. SIFs for modes I and II in this case can be calculated using the following equations, respectively.

$$\mathrm{K}_I = \frac{\sqrt{\pi a}\sigma_{yy}^{\infty}}{\cosh(\pi a)} \quad (4)$$

$$\mathrm{K}_{II} = \frac{2\varepsilon\sqrt{\pi a}\sigma_{yy}^{\infty}}{\cosh(\pi a)} \quad (5)$$

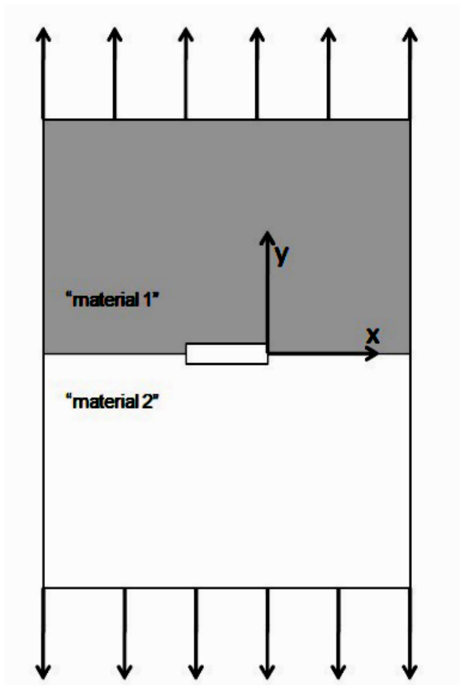


Figure 2. Midline crack in a bi-material continuous medium [35].

In order to avoid the stress fluctuations and to satisfy the continuity boundary conditions, a σ_{xx}^{∞} stress is necessary to be applied to the model, as shown in Figure 3.

$$for\left[\varepsilon_{xx}^{1} = \varepsilon_{xx}^{2}\right] \to \sigma_{xx}^{II\infty} = \frac{E_{II}}{E_I}\left(\frac{1-\nu_I^{2}}{1-\nu_{II}^{2}}\right)\sigma_{xx}^{I\infty} + \left[\frac{\nu_{II}}{1-\nu_{II}} - \frac{E_{II}}{E_I}\frac{\nu_I(1+\nu_I)}{1-\nu_{II}^{2}}\right]\sigma_{yy}^{\infty} \quad (6)$$

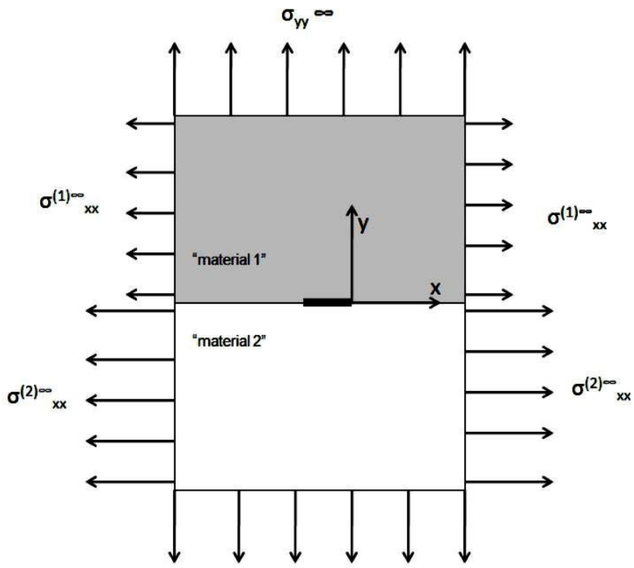


Figure 3. Additional loading required to satisfy continuity [35].

3. Verification of numerical model

A middle crack under the tensile force in a continuous isotropic medium was simulated in ABAQUS software employing the extended finite element method (XFEM). For this purpose, four-node rectangular elements were adopted for mesh generation, and linear elastic behavior was applied to the materials of the model. In order to have negligible induced displacements along the boundaries, the dimensions of the model were selected large enough compared to the crack length. The software input parameters for a single material are listed in Table 1.

The SIF values calculated by the software show a good agreement with the analytical predictions of Saouma (1994), as shown in Figure 4.

The simulation process was repeated for a single crack at the interface of two materials, as shown schematically in Figure 2. The software input parameters for a bi-material are listed in Table 2. The contours of stresses in the models with and without horizontal loading are shown in Figure 5.

According to Morioka (2010), due to the differences in the material characteristics and the type of loading, failure of the surface crack in a bi-material medium must be a hybrid mode, even when the loading is purely under mode I [35]. The values for K_I and K_{II} calculated by software and analytical predictions of Sun and Jih (1987) [37] are compared in Figure 6. A good agreement can be seen between the results of numerical and analytical solutions, especially for the K_I values.

Table 1. Software input data for a single material.

Parameter	Value
Young's modulus	5 GPa
Poisson's ratio	0.3
Crack length	10 mm
Plate dimensions	$30\times30m^2$
Tensile stress	$10-100MPa$
Borehole diameter	100 mm

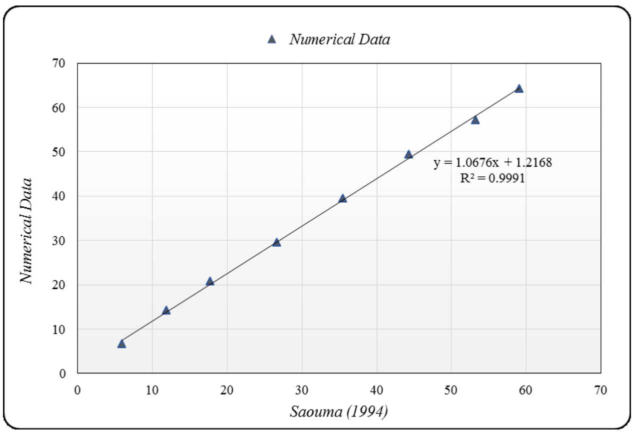
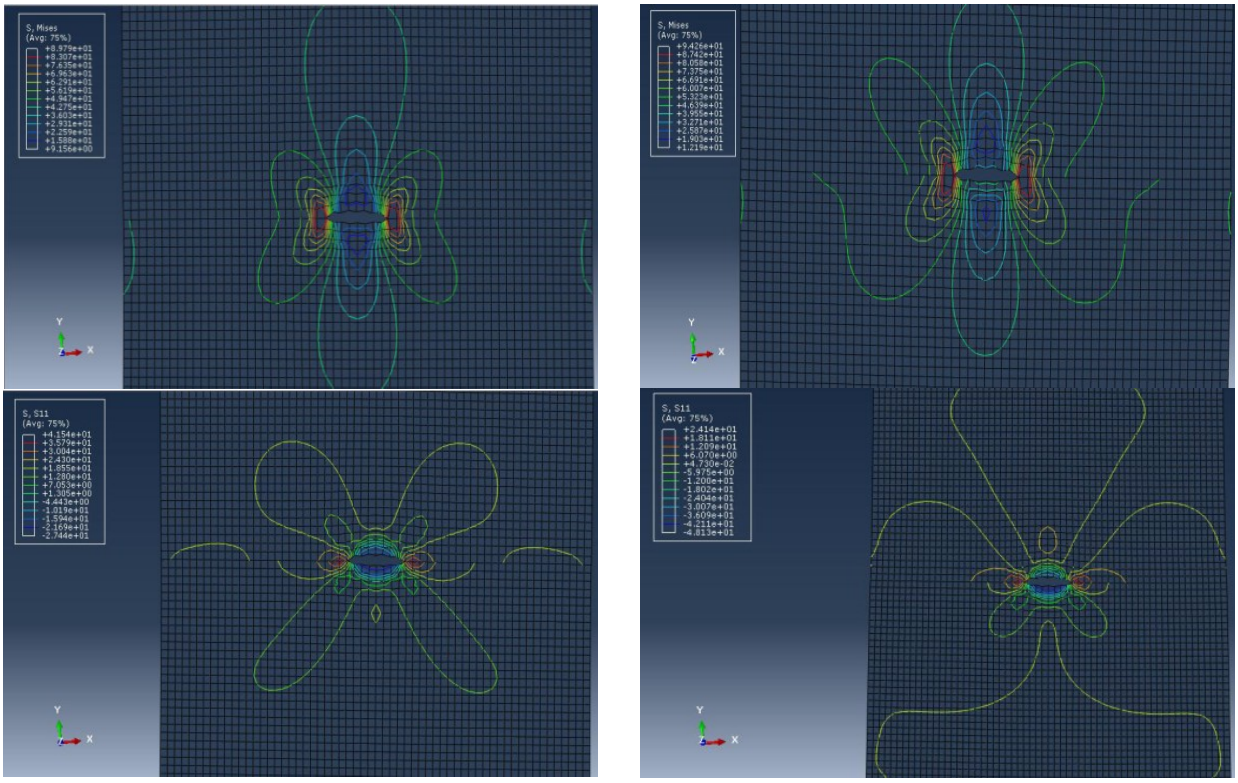


Figure 4. Comparison of numerical results and analytical predictions for K_I.

Table 2. Software input data for a bi-material.

Parameter	Value
Young's modulus of medium I	5 GPa
Poisson's ratio of medium I	0.3
Young's modulus of medium II	8 GPa
Poisson's ratio of medium II	0.25
Crack length	4.24 m
Plate dimensions	$30 \times 30 m^2$
Tensile stress	$10-100 MPa$
Material density of medium I	$1600 Kg/m^3$
Material density of medium II	$2700 Kg/m^3$
$\sigma_{xx}^{(1)\infty}$	$20 MPa$
ε	0.00845



a) With horizontal loading   b) Without horizontal loading

Figure 5. Contours of stresses around a single crack at interface of two materials.

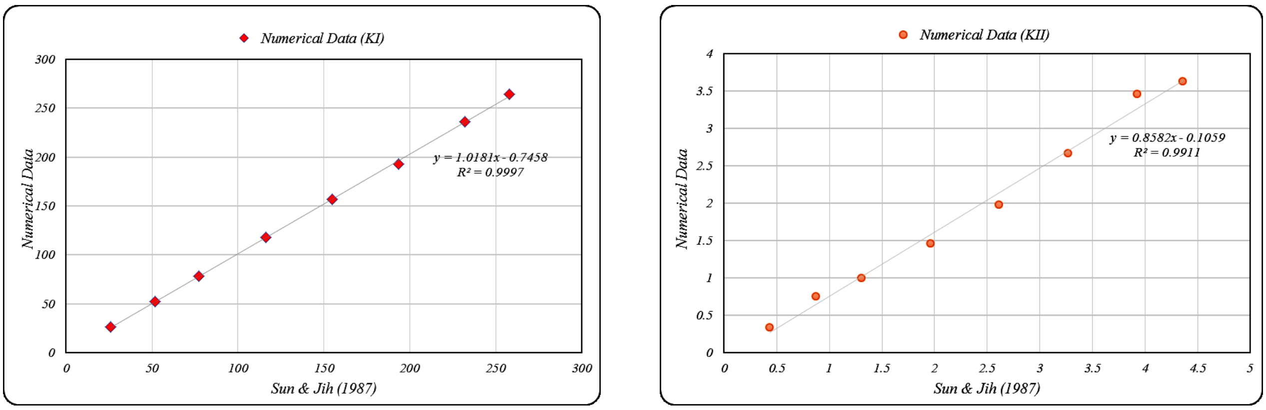


Figure 6. Comparison of values K_I and K_{II} obtained from analytical equations and numerical simulations.

4. Case study of numerical modeling

The Chadormalu open-pit iron mine, as one of the most important iron resources of Iran, is located in the Yazd province in the central part of the country. Two types of Chadormalu rocks, granite and diorite, were used for numerical modeling in this work. First, a borehole with the wall crack in each one of the rock types was modeled, and then the model was constructed with a crack on the boundary of the two materials. The linear elastic model was selected as the material behavior, and four-node rectangular elements were applied in order to discretize the domain. The model dimensions were adopted large enough to vanish the induced displacements along boundaries. The software input parameters are the field data, as shown in Table 3.

In Figure 7, the left hand side shows a schematic representation of the model built in ABAQUS software, while the right hand side shows the mesh generation of the whole model. The main point of the modelling lays in the fact that the crack length is so small compared to the borehole diameter. The drilling borehole is assumed to be drilled horizontally from the pit wall into the rock.

Table 3. Software input parameters for Chadormalu granite and diorite [38].

Granite		Diorite	
Parameter	**Value**	**Parameter**	**Value**
Elastic Modulus	35.29 *GPa*	Elastic Modulus	40.18 *GPa*
Poisson's ratio	0.27	Poisson's ratio	0.29
Borehole depth	0.1 m	Borehole depth	0.1 m
Rock density	2660 Kg/m^3	Rock density	3100 Kg/m^3
Porosity	10%	Porosity	10%
K_{IC}	44.4MPa*mm$^{1/2}$	K_{IC}	44.8 MPa*mm$^{1/2}$
Plate dimensions	$50 \times 50m^2$	Plate dimensions	$50 \times 50m^2$
Crack length	10 *mm*	Crack length	10 *mm*
Injection density	980 Kg/m^3	Injection density	980 Kg/m^3
Viscosity	1.865E-005 *Pa.s*	Viscosity	1.865E-005 *Pa.s*
Permeability	5E-010 *m/kPa.s*	Permeability	5E-010 *m/kPa.s*
Maximum tolerant stress	139.45 *MPa*	Maximum tolerant stress	149.33 *MPa*

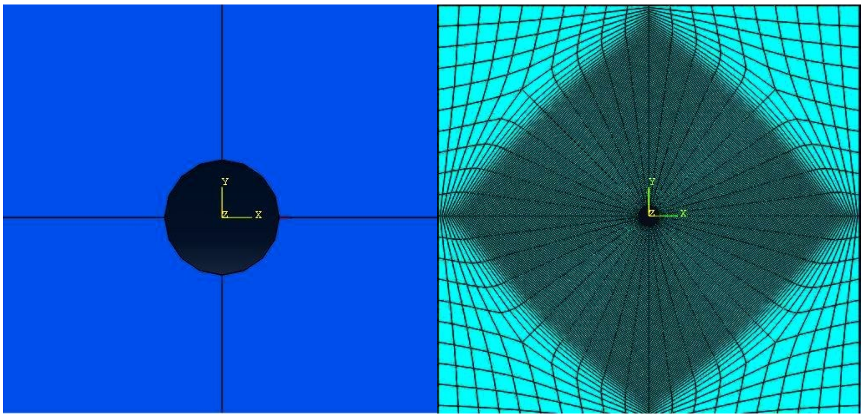


Figure 7. Schematic representation of the model and mesh generation.

5. Results and discussions

Variations in the crack length in different materials versus process time is shown in Figure 8. As shown in this graph, the crack propagation rate in the diorite is less than that in granite. Furthermore, the crack propagation rate in both rock types is less than that in the interface of two rocks.

Figure 9 shows the fluid pressure variations with crack lengths. As it is clear in this figure, the fluid pressure for propagation of a crack in the interface of diorite and granite is significantly less than the fluid pressure required to propagate the same crack length in any of those rocks.

The variations in K_I as a function of crack length is plotted in Figure 10. K_I decreases with increase in the crack length, and with the same geometry for all three cases, this reduction occurs with almost the same rate. Furthermore, due to the greater stiffness of diorite and granite compared to their interface, it can be seen that the K_I values in these materials are higher than the interface.

Figure 11 demonstrates the total energy variations in terms of the implementation time of the injection process. As expected, due to the higher strength of diorite, the range of variation of energy for crack propagation in diorite is more than granite, and in granite, it is more than the crack in the interface of the two materials.

Furthermore, the variations of energy release rate (G) in terms of the crack length is illustrated in Figure 12. As the G value has a direct relation with the K value, it decreases with increase in the crack length. Again, for a given crack length, the G value required for interface in a bi-material is less than the values required for both single materials.

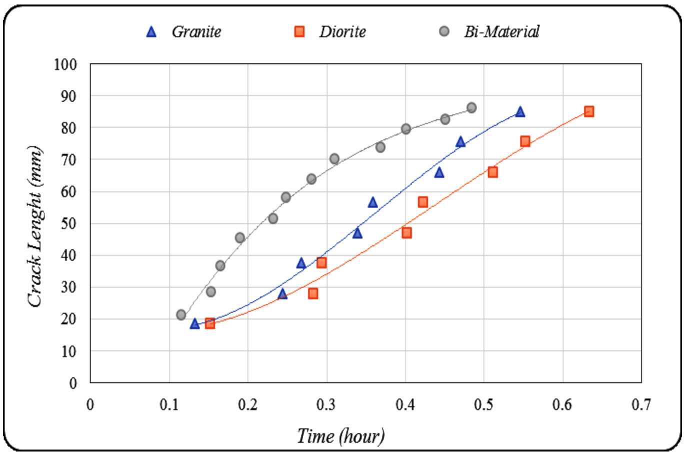


Figure 8. Crack length variations in terms of the process time.

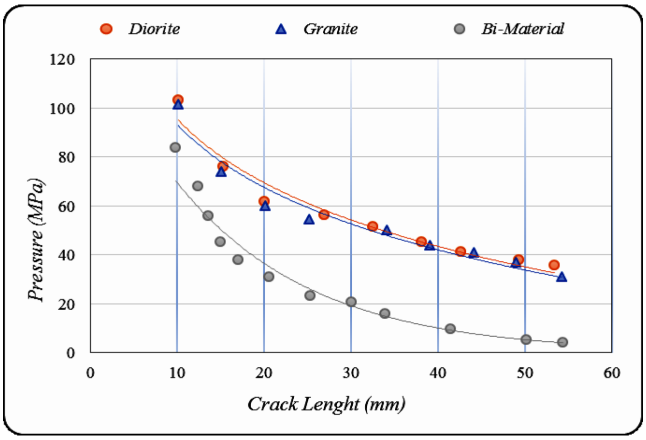


Figure 9. Pressure changes in terms of the crack length during the process.

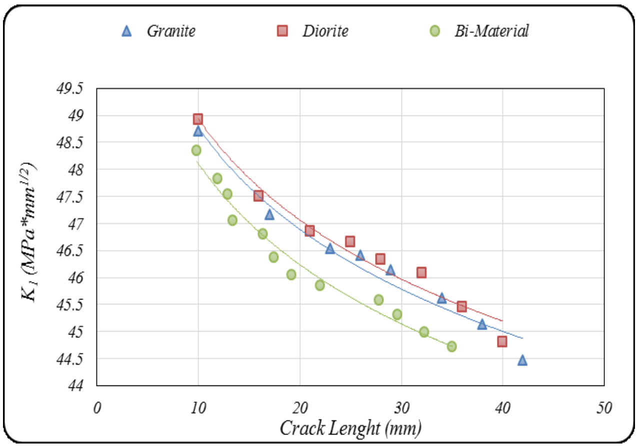


Figure 10. Variations in K_I as a function of crack length.

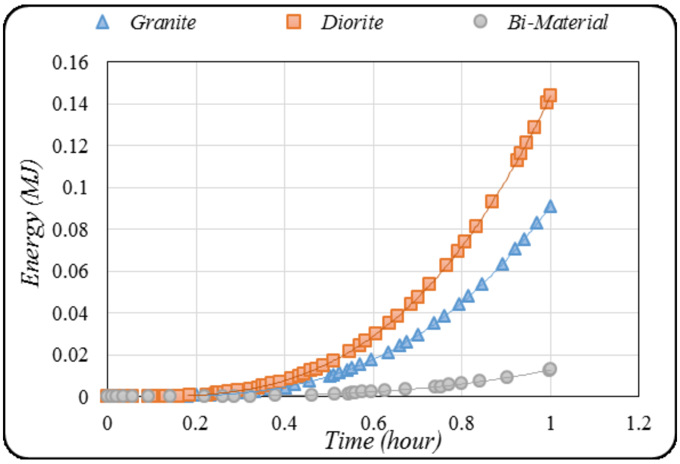


Figure 11. Variations of energy with processing time.

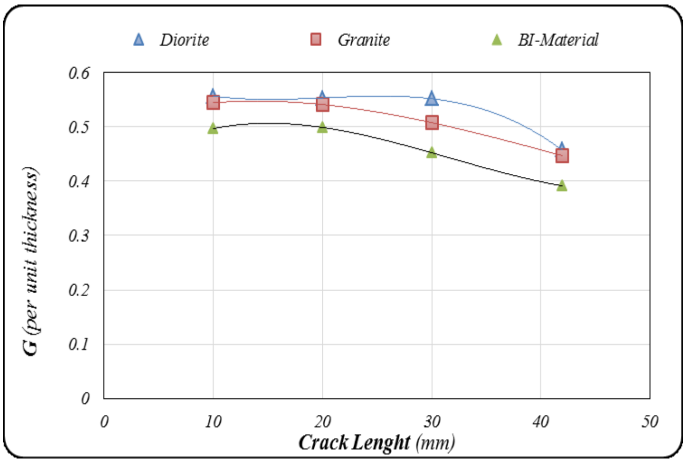


Figure 12. Variations of G values versus crack length.

6. Conclusions

The problem of crack propagation along a bi-material interface was modeled by numerical modeling, employing the XFEM method for high-order non-linearity of induced stress fields. The energy method was implemented to obtain the stress intensity factor and energy release rate through applying J integral around the crack tip. The main findings of this research work are as follow:

- In simulation of bi-materials, the difference in the inherent characteristics of the materials induces an asymmetric horizontal stress at their interface. Therefore, the fluctuations due to induced stresses could be prevented by placing different horizontal stresses in the opposite directions.
- With the same geometry, at a given time, the crack propagation at the interface of bi-material is more than the single material medium. In addition, regarding the single material medium, the higher the rock strength, the lower is the crack length propagation.
- The fluid pressure required for propagation of a crack at the interface of bi-material is less than the fluid pressure required to propagate the same crack length in any of those single materials.
- When dealing with a bi-material medium, the crack propagation certainly occurs on the boundary between the two materials, and hence, if the purpose is to measure the *in situ* stresses, the measurement should not be performed on the boundary between the two materials.

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استفاده از روش المان محدود توسعه‌یافته در به کارگیری روش انرژی برای شبیه‌سازی رشد ترک ناشی از تزریق در توده سنگ معدن چادرملو

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ارسال ۲۰۱۸/۴/۲۵، پذیرش ۲۰۱۸/۷/۲۸

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چکیده:

مکانیک شکست یک علم کاربردی در مطالعه دقیق رفتار مواد سنگی به حساب می‌آید. شناسایی و ارزیابی رفتار ناپیوستگی‌های توده سنگ تحت فشار تزریق نقش مهمی در مدل‌سازی عددی پروژه‌های مرتبط با مکانیک سنگ دارد. اهمیت مکانیسم‌های مرتبط با شروع و انتشار ترک‌های ناشی از شکست هیدرولیکی منجر به تحقیقات قابل توجه‌ای روی این پدیده شده است. در این پژوهش ، فرآیند انتشار ترک روی دیوار گمانه حفر شده در ساختارهای سنگی تک ماده‌ای و دو ماده‌ای، با استفاده از روش المان محدود توسعه‌یافته، در نرم‌افزار آباکوس شبیه‌سازی شده است. به منظور محاسبه فاکتور شدت تنش و نرخ انتشار انرژی در اطراف ترک از روش انرژی استفاده شده است. سپس این روش برای مطالعه رشد ترک در دو نوع سنگ (دیوریت و گرانیت) معدن سنگ آهن چادرملو واقع در بخش مرکزی ایران استفاده شده است. نتایج این تحقیق نشان می‌دهد که در شرایط هندسی یکسان، احتمال رشد ترک در مرز بین دو ماده سنگی بیشتر از رشد ترک در داخل یک ماده سنگی واحد است؛ بنابراین، در انجام تست شکست هیدرولیکی به منظور تعیین تنش‌های برجای زمین، انجام تست در مرز بین دو ماده سنگی توصیه نمی‌شود.

کلمات کلیدی: مکانیک شکست، محیط دو ماده‌ای، روش‌های انرژی، روش المان محدود توسعه‌یافته.