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王宽诚教育基金会简介

王宽诚先生(1907—1986)为香港著名爱国人士,热心祖国教育事业,生前为故乡宁波的教育事业做出积极贡献。1985 年独立捐巨资创建王宽诚教育基金会,其宗旨在于为国家培养高级技术人才,为祖国四个现代化效力。

王宽诚先生在世时聘请海内外著名学者担任基金会考选委员会和学务委员会委员,共商大计,确定采用“送出去”和“请进来”的方针,为国家培养各科专门人才,提高内地和港澳高等院校的教学水平,资助学术界人士互访以促进中外文化交流。在此方针指导下,1985、1986 两年,基金会在国家教委支持下,选派学生 85 名前往英、美、加拿大、德国、瑞士和澳大利亚各国攻读博士学位,并计划资助内地学者赴港澳讲学,资助港澳学者到内地讲学,资助美国学者来国内讲学。正当基金会事业初具规模、蓬勃发展之时,王宽诚先生一病不起,于 1986 年年底逝世。这是基金会的重大损失,共事同仁,无不深切怀念,不胜惋惜。

1987 年起,王宽诚教育基金会继承王宽诚先生为国家培养高级技术人才的遗愿,继续对中国内地、台湾及港澳学者出国攻读博士学位、博士后研究及学术交流提供资助。委请国家教育部、中国科学院和上海大学校长钱伟长教授等逐年安排资助学术交流的项目。相继与(英国)皇家学会、法国科研中心、德国学术交流中心、法国高等科学研究院等著名欧洲学术机构合作,设立“王宽诚(英国)皇家学会奖学金”、“王宽诚法国科研中心奖学金”、“王宽诚德国学术交流中心奖学金”、“王宽诚法国高等科学研究院奖学金”,资助具有副教授或同等职称以上的中国内地学者前往英国、法国、德国等地的高等学府及科研机构进行为期 2 至 12 个月之博士后研究。

王宽诚教育基金会过去和现在的工作态度一贯以王宽诚先生倡导的“公正”二字为守则,谅今后基金会亦将秉此行事,奉行不辍,借此王宽诚教育基金会《学术讲座汇编》出版之际,特简明介绍如上。王宽诚教育基金会日常工作繁忙,基金会各位董事均不辞劳累,做出积极贡献。

前　言

王宽诚教育基金会是由已故全国政协常委、香港著名工商企业家王宽诚先生(1907—1986)出于爱国热忱，出资一亿美元于1985年在香港注册登记创立的。

1987年,基金会开设“学术讲座”项目,此项目由当时的全国政协委员、历任第六、七、八、九届全国政协副主席、著名科学家、中国科学院院士、上海大学校长、王宽诚教育基金会贷款留学生考选委员会主任委员兼学务委员会主任委员钱伟长教授主持。由钱伟长教授亲自起草设立“学术讲座”的规定,资助内地学者前往香港、澳门讲学,资助美国学者来中国讲学,资助港澳学者前来内地讲学,用以促进中外学术交流,提高内地及港澳高等院校的教学质量。

本汇编收集的文章,均系各地学者在“学术讲座”活动中的讲稿,文章内容有科学技术,有历史文化,有经济专论,有文学,有宗教和中国古籍研究等。本汇编涉及的学术领域颇为广泛,而每篇文章都有一定的深度和广度,分期分册以《王宽诚教育基金会学术讲座汇编》的名义出版,并无偿分送国内外部分高等院校、科研机构和图书馆,以广流传。

王宽诚教育基金会除资助“学术讲座”学者进行学术交流之外,还资助由国内有关高等院校推荐的学者前往欧、美、亚、澳等参加国际学术会议,出访的学者均向所出席的会议提交论文,这些论文亦颇有水平,本汇编亦将其收入,以供参考。

王宽诚教育基金会学务委员会

凡　　例

（一）编排次序

本书所收集的王宽诚教育基金会学术讲座的讲稿及由王宽诚教育基金会资助学者赴欧、美、亚、澳等参加国际学术会议的论文均按照文稿日期先后或文稿内容编排刊列，不分类别。

（二）分期分册出版并作简明介绍

因文稿较多，为求便于携带，有利阅读与检索，故分期分册出版，每册 150 页至 240 页不等。为便于读者查考，每篇学术讲座的讲稿均注明作者姓名、学位、职务、讲学日期、地点、访问院校名称。内地及港、澳学者到欧、美、澳及亚洲的国家和地区参加国际学术会议的论文均注明学者姓名、参加会议的名称、时间、地点和推荐的单位。上述两类文章均注明由王宽诚教育基金会资助字样。

（三）文字种类

本书为学术性文章汇编，均以学术讲座学者之讲稿原稿或参加国际学术会议者向会议提交的论文原稿文字为准，原讲稿或论文是中文的，即以中文刊出，原讲稿或论文是外文的，仍以外文刊出。

目　录 CONTENTS

王宽诚教育基金会
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Numerical Simulation on Excavation Damaged Zone in Fractured Rockmass Under Coupled THM Conditions

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Abstract: The creation of an excavation damaged zone (EDZ) is expected around all man-made openings in civil engineering, in underground mining, and in petroleum engineering. The EDZ may vary the physical, mechanical, and hydraulic properties of rockmass, and in turn dominate the evolution of EDZ under coupled thermal, hydraulic and mechanical (THM) environments. Understanding the development of EDZ under coupled THM conditions is of great importance for evaluating the engineering stability and safety, and for optimizing the supporting parameters. The work begins an introduction to the coupled THM model for the rock damage, which is proposed when the damage variable is incorporated into the classic thermohydroelastic model according to elastic damage theory. Next, the model is numerically implemented with finite element method by employing a numerical package called COMSOL multiphysics (CM), and is also validated against some existing experimental observations. Finally, the model is used to simulate the formation and development of EDZ under coupled THM environments, and the effect of rockmass heterogeneity, potential THM boundary conditions on the coupled THM responses of rock mass is examined.
Key words: fractured rockmass, excavation damaged zone (EDZ), thermal-hydraulic-mechanical (THM) coupling, numerical simulation

1 Introduction

In enhanced geothermal systems, as in reservoirs for the sequestration of CO_2, radioactive

* 朱万成,教授,东北大学资源与土木工程学院。由王宽诚教育基金会资助,于2010年10月赴印度新德里参加"国际岩石力学学会会议暨第六届亚洲岩石力学大会",此为其向大会递交的论文。

waste repositories, petroleum reservoirs, and other subsurface engineered facilities, the excavation damaged zone (EDZ) around the underground opening is influenced in both the short- and long-term by thermal-hydraulic-mechanical (THM) behavior of fractured rockmass. The coupled THM numerical models used in rock mechanics can be traced back to early 1980s, when many models were proposed based on the extension of Biot's theory of consolidations. Beginning from 1990s, under the formwork of international cooperative project entitled DECOVALEX, a number of benchmark tests (BMT) and test cases (TC) have been carried out in order to support development of computer simulators for THM processes in geological systems[1-2]. Up to now, most numerical codes are still based on the assumption of elasticity and plasticity of rocks, or based on discrete approach where only a limited number of fractures are included to represent the fractured rockmass, thus the propagation of existing fractures, as well as the initiation of new fractures in rockmass, is usually ignored. However, both the hydraulic and thermal processes are sensitive to fracture initiation and propagation. Under the coupling of complex THM processes the existing fractures may propagate and some new fractures may initiate, which in turn alters the thermal and hydraulic processes. Therefore, it is quite significant to incorporate the damage processes of rock in the numerical models in order to characterize the coupled THM response of fractured rocks, especially during the formation and development of EDZ.

In view of this, the authors have recently developed a damage-based THM model to study the coupled THM process during rock failure[3], which makes it a competitive candidate for characterizing the THM response of the EDZ around underground openings. To this end, it is to numerically study the development of EDZ under coupled THM condition that defines the objective of this work.

2 Governing Equations

In this study, the conservation equations for mass and momentum are derived on the macroscopic scale (all variables are averaged over the REV of the medium) for a saturated, porous medium. Fractures are treated as a "porous medium" separated from the rock matrix by using well-refined elements in a finite-element mesh. Therefore, the basic balance equations are the same for rock matrix and fracture materials, while the constitutive relations differ. A basic assumption is that a macroscopic approach can be applied, meaning that the porous medium can be treated as a quasi-continuum where volume-averaged quantities replace the local ones. With this approach and these assumptions, two balance equations for solid and fluid and a number of constitutive relations are required for a full description of the coupled THM state. The mathematical formulation for the fully coupled THM system is summarized as follows.

2.1 Mechanical Equilibrium and Damage Evolution Equations

Initially the porous medium is assumed elastic, with constitutive relationship defined by a generalized Hook's law. In this regard, a modified Navier equation, in terms of displacement under a combination of changes of applied stresses (positive for tension), fluid pressures (negative for suction) and temperature change is expressed as

$$Gu_{i,jj} + \frac{G}{1-2\nu}u_{j,ji} - \alpha p_{,i} - K'\alpha_T T_{,i} + F_i = 0, \tag{1}$$

where $u_i (i = x, y, z)$ is displacement, G shear modulus, ν the drained Poisson's ratio, F_i the components of the net body force in the i-direction ($i = x, y, z$), α_T coefficient of volumetric expansion of the bulk medium. $\alpha(\leqslant 1)$ is Biot's coefficient depending on the compressibility of the constituents and can be defined as $\alpha = 1 - K'/K_s$, where K_s is the effective bulk modulus of the solid constituent, and $K' = 2G(1+\nu)/3(1-2\nu)$ is the drained bulk modulus of the porous medium.

As illustrated in Fig. 1, the damage in tension or shear initiates when its state of stress satisfies the maximum tensile stress criterion or the Mohr-Coulomb criterion, respectively, as expressed by

$$F_1 \equiv \sigma_1 - f_{t0} = 0 \text{ or } F_2 \equiv -\sigma_3 + \sigma_1[(1+\sin\phi)/(1-\sin\phi)] - f_{c0} = 0, \tag{2}$$

where f_{t0} and f_{c0} are uniaxial tensile and compressive strength, respectively, σ_1 and σ_3 are major and minor principal stresses, respectively, ϕ internal frictional angle, and F_1 and F_2 are two damage threshold functions.

According to the theory of elastic damage, the elastic modulus of an element degrades monotonically as damage evolves, and the elastic modulus of damaged material is expressed as follows:

$$E = (1 - D)E_0, \tag{3}$$

where D represents the damage variable, and E and E_0 are the elastic moduli of the damaged and the undamaged material, respectively. In the current method, the element as well as its damage is assumed isotropic. Under any stress conditions, the tensile strain criterion is applied preferentially. According to Fig. 1, the damage variable can be calculated as

$$D = \begin{cases} 0, & F_1 < 0 \text{ and } F_2 < 0, \\ 1 - |\varepsilon_{t0}/\varepsilon_1|^n, & F_1 = 0 \text{ and } dF_1 > 0, \\ 1 - |\varepsilon_{c0}/\varepsilon_3|^n, & F_2 = 0 \text{ and } dF_2 > 0, \end{cases} \tag{4}$$

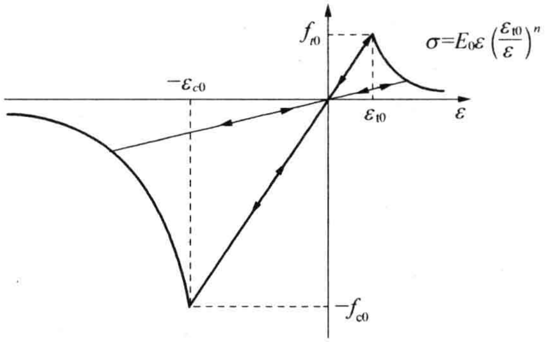


Fig. 1 Elastic damage-based constitutive law of elements under uniaxial stress condition (f_{t0} and f_{c0} are uniaxial tensile strength and uniaxial compressive strength, respectively).

where ε_{t0} and ε_{c0} are maximum tensile principal strain and maximum compressive principal strain when damage occurs, respectively, ε_1 and ε_3 are the first and the third principac, respectively, and n is a constitutive coefficient specified as 2.0.

2.2 Flow Equation

If the fluid flow follows the Darcy's law, the conservation equation of fluid can be expressed as[4-5]

$$c_1 \frac{\partial \varepsilon_v}{\partial t} - c_2 \frac{\partial T}{\partial t} + c_3 \frac{\partial p}{\partial t} = \nabla \left(\frac{k}{\mu_1} (\nabla p + \rho_1 g \ \nabla z) \right), \tag{5}$$

where $c_1 = 1 - K'/K_s$, $c_2 = \phi \alpha_1 + (1-\phi)\alpha_s - \alpha_T K'/K_s$, $c_3 = \phi/\beta_1 + (1-\phi)/K_s$, ε_v the volume strain, μ_1 the dynamic fluid viscosity ($\mathrm{N \cdot s/m^2}$), k the intrinsic permeability in a general continuum ($\mathrm{m^2}$), ρ_1 the liquid density ($\mathrm{kg/m^3}$), z the vertical coordinate, g gravitational acceleration ($\mathrm{m/s^2}$), ϕ porosity, and β_1 denotes the bulk modulus of fluid ($\mathrm{Pa^{-1}}$).

2.3 Energy Conservation Equation

Due to the assumption of thermal equilibrium between the fluid and solid phases, the heat energy balance equation over an REV can be expressed in terms of a single equation which neglects the terms representing the interconvertibility of thermal and mechanical energy as[4]

$$(\rho C)_M \frac{\partial T}{\partial t} + (T_0 + T)\alpha_1\beta_1 \ \nabla \cdot \frac{k}{\mu}(\nabla p + \rho_1 g \ \nabla z) - (T_0 + T)K'\alpha_T \frac{\partial \varepsilon_v}{\partial t}$$

$$- \frac{(\rho C)_M}{\phi} \frac{k}{\mu}(\nabla p + \rho_1 g \nabla z) \cdot \nabla T = \lambda_M \nabla^2 T, \tag{6}$$

where T_0 is the absolute reference temperature in stress-free state (K), ρ_0 reference mass density of solid ($\mathrm{kg/m^3}$), $(\rho C)_M$ specific heat capacity of the fluid-filled medium ($\mathrm{J/m^3 \cdot ℃}$), and λ_M is thermal conductivity of the fluid-filled medium ($\mathrm{J/s \cdot m \cdot ℃}$).

Equations (1), (4), (5) and (6) represent a set of fully coupled non-linear equations governing the thermo-poroelastic response of damaged saturated medium. The equations account for thermodynamically coupled, heat and mass transfer, mechanical and thermal compressibility of the constituents, and in particular the damage evolution of the medium.

2.4 Effect of Damage on THM Parameters

The porosity is closely dependent on the stress conditions, which is given by RUTQVIST and TSANG[6]:

$$\phi = (\phi_0 - \phi_r)\exp(\alpha_\phi \bar{\sigma}_v) + \phi_r, \tag{7}$$

where ϕ_0 is porosity at zero stress, α_ϕ stress sensitivity coefficient, which is $5.0 \times 10^{-8}\ \mathrm{Pa^{-1}}$[6], ϕ_r residual porosity at high stress, and $\bar{\sigma}_v$ is the effective mean stress (with tension positive and in Pa), being calculated as $\bar{\sigma}_v = (\sigma_1 + \sigma_2 + \sigma_3)/3 + \alpha p$. Besides, the permeability is correlated to the porosity according to the following exponential function:

$$k = k_0\,(\phi/\phi_0)^3 \exp(\alpha_k D), \tag{8}$$

where k_0 is the zero-stress permeability, and α_k is 5.0, being called damage-permeability coefficient to indicate the effect of damage on the permeability.

The effect of damage on thermal conduction is not clear. Simply, in the similar form as that of permeability, it is given as

$$\lambda_s(T,\, D) = \lambda_s(T)\exp(D/\alpha_T), \tag{9}$$

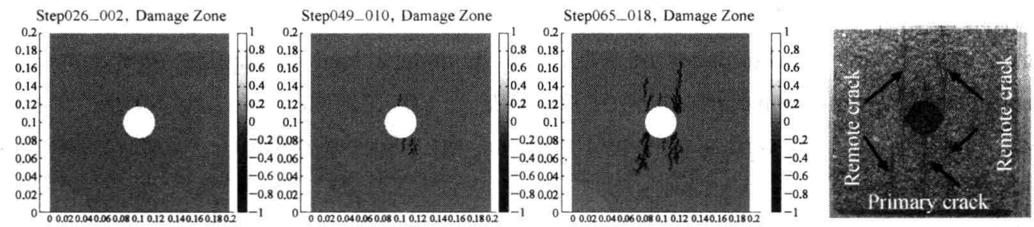
where α_T is a coefficient to reflect the effect of damage on the thermal conductivity.

The above governing equations are nonlinear partial differential equations (PDEs) with second order for space and first order for time. The non-linearity appears both in space and time domain, and therefore these equations are not possible to be solved analytically. In this respect, the complete set of coupled equations is implemented, and solved by using COMSOL multiphysics[7], a powerful PDE-based multiphysics modelling environment.

3 Validation of the Model for Modelling the Rock Damage

In this section, the failure process of granite tested by CARTER, *et al.* [8] is numerically simulated with the proposed model in order to validate the capability of model in capturing the damage zone of rock. The granite has a Young's modulus of 71. 3 GPa, a uniaxial compressive strength of 226. 0 MPa, a tensile strength of 14. 0 MPa, and a Poisson's ratio of 0. 25. The rock is assumed to be heterogeneous with its mechanical properties defined by a Weibull distribution.

For this example, even if the geometry and loading condition are relatively simple, the damage mechanisms around the hole are so complex that not all numerical models can reproduce it. Figure 2 shows the damage zone distribution simulated with the numerical simulation, in which the black and white indicate the tensile and shear damage, respectively while grey denotes the elastic zone. It is shown that the failure patterns as characterized as the initiation and

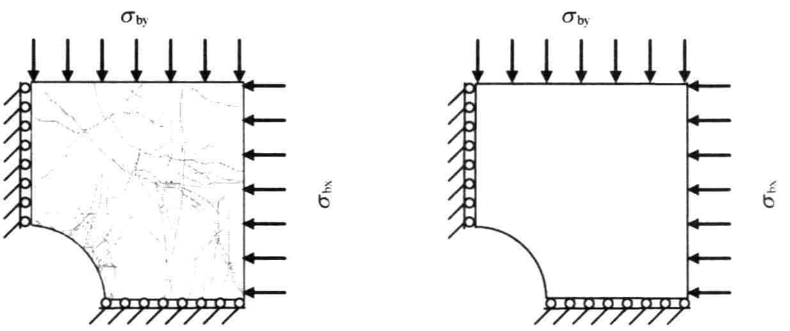


(a) Step 26 (b) Step 49 (c) Step 65 (d) Experimental

Fig. 2 Development of damage zone around circular hole (numerical results (a) - (c) and experimental results (d)[8]) propagation of primary cracks and remote cracks are vividly reproduced with the numerical simulation, and the failure pattern simulated with this model compares well with the experimental observation (see Fig. 2(d)). Thus, it is reasonable to conclude that the proposed model is effective in capturing the damage process of heterogeneous rock.

4 EDZ Development under Coupled THM Conditions

In this section, the simulation on the near-field model domain, as applied in DECOVALEX project[9], is conducted in order to illustrate the capability of the proposed model in studying the evolution of EDZ under coupled THM conditions. The sizes of the two models are both 3.42 m by 3.42 m (three times the tunnel radius). Two cases, including a homogenous model and a heterogeneous one (fracture network model), are presented to discuss the effect of heterogeneity of rock mass (see Fig. 3). As shown in Fig. 3(a), the fractured rock is characterized by using the digital image-based technique by using the image of this fractured rock that was derived from fracture mapping by Ann Bckstrm of Royal Institute of Technology, Sweden at the Äspö Hard Rock Laboratory[9].

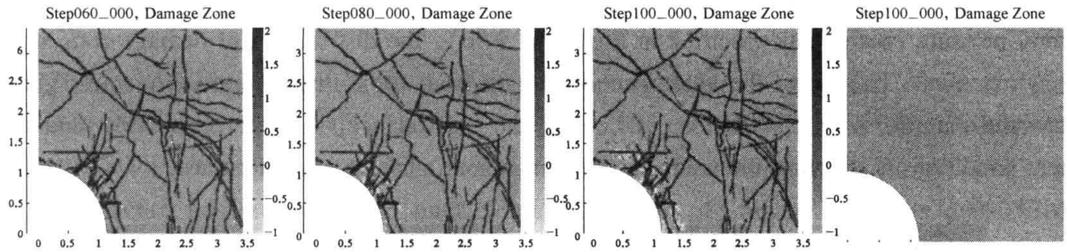


(a) Fracture network model (b) Homogeneous model

Fig. 3 Two cases used in the numerical simulation of EDZ

The initial pre-excavation conditions are represented by *in situ* stresses, temperature and fluid pressure at a depth of 500 m in crystalline rocks: an initial vertical stress of 13.2 MPa, a horizontal stress of 32.1 MPa, a temperature of 25 ℃, and a fluid pressure of 5.0 MPa. In order to simulate the development of EDZ, the boundary load is applied in monotonically increasing mode, with an increment of 0.321 MPa and 0.132 MPa per step for the boundary stresses in horizontal and vertical direction, respectively. So the 100th step corresponds to the post-excavation state.

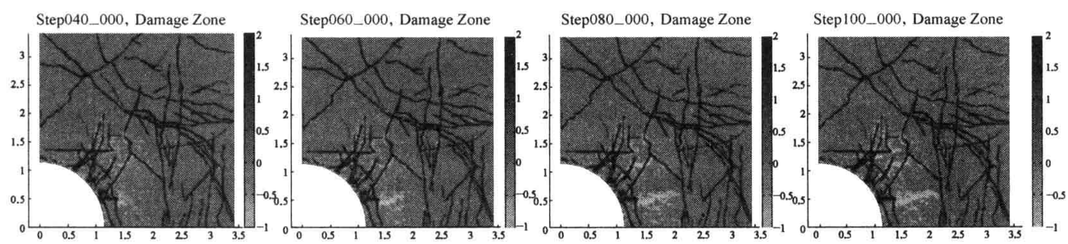
Figures 4 (a)-(c) and Figure 4(d) show the damage zone distribution of the heterogeneous model and homogeneous model, respectively. It is shown that, for the homogeneous model, the damage zone is distributed in top left corner, which is related to the *in-situ* stress conditions, while the damage zone of the fractured model, which is apparently controlled by the existing fractures, distributing mainly around the fractures. This denotes that the damaged zone distribution becomes very complex due to the existence of fractures, so exactly characterizing the spatial distribution of fractures is a key issue to forecast the formation and development of damaged zone. When we compare this simulation result with those simulated with the elastoplastic cellular automata code[10], it is found that the distributions of damaged zone are similar, however, some differences still exist, which may be related to the difference of the constitutive relations being used. It denotes that forecast of damaged zone when fractures are considered is much more difficult, which is related to the models to be used and still needs further study.



(a) Step 60 (b) Step 80 (c) Step 100 (d) Step 100

Fig. 4 Distribution of damage zone of heterogeneous model (a)-(c) and the homogenous model (d)

It should be pointed out that, in Fig. 4, the effect of temperature and fluid pressure is taken into account only as a boundary condition for the solid mechanics analysis. In this regard, it is very necessary to go further to incorporate the effect of temperature and porous pressure on damage. The outer boundary of the model considered here has an original temperature of 25 ℃ and a fluid pressure of 5.0 MPa. A fluid pressure of 5.5 MPa, and a temperature of 35 ℃ due to the radiation of nuclear wastes, is specified at the inner boundary, respectively. As shown in Fig. 5, due to the effect of temperature and fluid pressure, the damage zone extended further. Evidently, the increase of the temperature and fluid pressure induce the further tensile damage around the opening. This indicates that it is very important to consider the THM coupling in order to characterize the damage zone around the underground openings.



(a) Step 40 (b) Step 60 (c) Step 80 (d) Step 100

Fig. 5 Distribution of damage zone of fracture network model under coupled THM conditions

Another very important factor that affects the excavation damage zone is the geo-stress condition. In this respect, in order to examine the effects of the lateral pressure coefficient λ ($\lambda = \sigma_{bx}/\sigma_{by}$) on the progressive fracturing process, a range of magnitudes of λ from 0.1 to 10 was applied to the model. For the cases presented in Fig. 4 – 5, as a matter of fact, the lateral pressure coefficient λ of 13.2/32.1 = 0.41 is specified.

Figure 6 shows the damage zone distribution for other magnitude of λ. It is found that the distribution of damage zone is closed related to the direction of the maximum principal stress. When $\lambda < 1$, as shown in Fig. 6(a), the damage zone is mainly distributed at the top-left half of the model. In contrast, when $\lambda > 1$, as shown in Fig. 6 (b), the damage at bottom-right half of the model domain is much concentrated. If the medium is homogeneous, for the reciprocal lateral pressure coefficients specified in Fig. 6 (a)–(b), the distribution of damage zone would be symmetrical. However, the heterogeneity due to anisotropic distribution of fractures greatly alters the damage zone distribution, indicating the significance of fracture networks and geo-stress condition in affecting the excavation damage zone in fractured rock mass.

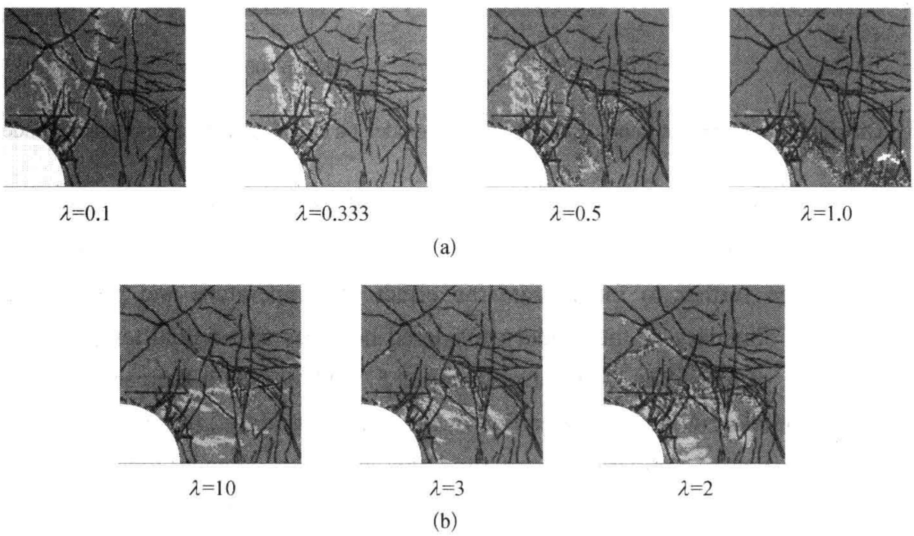


Fig. 6 Distribution of damage zone of fracture network model with different lateral pressure coefficient λ under coupled THM conditions

5 Conclusions

This paper contributes to studying the development of EDZ in fractured rock mass using a coupled THM model with damage process incorporated. The numerical simulation indicates that the damage mechanics-based model is capable of representing the characteristics of damage zone in fractured rock mass. With regard to the EDZ around the fractured rockmass, the temperature and fluid pressure, as well as the geo-stress condition, have a significant effect on the evolution of damage zone. Therefore, it is absolutely necessary to consider THM coupled interactions in order to correctly evaluate the development of damage zone in fractured rockmass.

Although only an elastic damage-based model is used to characterize the EDZ, it really reveals the important effects of the heterogeneity and damage on the coupled THM responses of the fractured rock mass. Of course, it should be noted that, due to the complexity of rockmass heterogeneity and of involved coupled THM environments, the effect of each coupling parameter on simulation results needs to be studied further.

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