Numerical Simulation of fracturing process around boreholes under static-dynamic loads by coupling two FEM models and damage mechanics

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Abstract: The fracture propagation process around the borehole under the static-dynamic loading is simulated by considering the inhomogeneity of rock material and statistic damage mechanics, and coupling COMSOL with Matlab. For some factors such as inhomogeneity of strength, layout of holes and loading order, simulations are conducted. The result provides some helps for a computer aided analysis of the blasting design in tunnel drivage.

Keywords: rock failure, damage mechanics, numerical simulation, rock blasting, tunnel drivage

1. Introduction

Many researchers have investigated the failure process of rock using the damage evolution mechanism under various loads [1-8]. To simulate and model the failure process around single borehole in rock mass, various numerical methods such as FEM, UDEC, FLAC, DEM, DDA and combined methods were used.
The induced damage zone around the excavation was simulated under different lateral pressure coefficients based on the general damage model for heterogeneous rock mass for finite element analysis and by taking the dynamic stress redistribution due to excavation into account [4].

The single-hole blast-induced damage in a granitic outcrop was assessed through both controlled experiments and numerical simulations with combining finite and discrete element method (FEM-DEM) [9]. The combined action of stress waves and gases along a single borehole leads to significant damage originating from the explosive initiation point, when this is strongly confined and to only mild damage when low confinement.

Ling X [10] used the material-point method in conjunction with a decohesive failure model and a single pressure pulse as the source of stress waves to simulate the effect of blasting in single borehole on the tunnel failure. He considered that the rock mass entirely failed in compression at the beginning of explosion cylindrically and tensile cracks occurred radially in the periphery of plastic compressive region with time elapsing.

Using the material point method (MPM), Hao et al. [11, 12] also developed an anisotropic damage model to analyze the granite under blast loads by taking into account pre-existing cracks and joints in rock, where the damage was accumulated by degrading the effective material stiffness and strength.

The blast-induced hard rock fracture propagation was simulated using a numerical analysis based on the extended finite element method, where cracks around a single borehole were mainly developed in the regular radical direction [13].

A researcher [14] applied a constitutive model considering the dynamic compressive and tensile failure to analyze the blasting-induced fracture propagation in coal masses using LS-DYNA software and to discuss crack connections among bedding planes, based on the Kachanov equation.

Assuming that the rock was composed of a number of microelements with different mechanical properties, the initiation and growth of cracks and fractures in rock structure were studied by Tang CA [15].

Some researchers compared the simulated distribution of stress concentration factors with the known analytical solutions to successfully simulate the borehole progressive failure processes under a variety of geometrical and loading conditions, using RFPA2D [17-20].

In order to present the fracture progressive process of rock, they used the method where the loading time was divided into several steps and the result of previous step set as the initial condition for next step, and made the calculation with considering the inhomogeneity of rock property as Weibull statistic distribution. This tool is proper to simulate the total failure process not only in a rock specimen but in the solid material structure similarly to the experimental observation, however there is a lack in setting the loading and boundary conditions.

From above, coupling FEM with the statistic method to present the anisotropy of rock may give a more detailed simulation of the failure process around boreholes in rock mass.
This study provides a method for simulating the crack propagating process around boreholes in rock mass under the static and dynamic loads such as blasting by controlling the computation of two FEM models by MATLAB.

2. Simulation principle and method

2.1. Heterogeneity of rock material

It assumes that rock consists of continuously distributed micro-elements and its damage is expressed by the difference of bearing capacity in micro-elements.

From the view point of micro world, every element (micro particle) composing the rock is uniform and continuous in itself, whereas the mechanical properties of individual element such as Young’s modulus, strength and Poisson’s ratio may be different each other. The properties of element including many drawbacks are greatly low and it including less or little drawbacks is similar to each other [16, 17, 18].

Such this scattering of the mechanical property in rock can be demonstrated using Weibull’s statistic law [15].

\[
\Phi(u) = \frac{m}{u_0} \left( \frac{u}{u_0} \right)^{m-1} e^{-\left( \frac{u}{u_0} \right)^m}
\]

(1)

In which \(u\) is the property of element (strength, elastic modulus and so on), \(u_0\) is the mean value of property and \(m\) is the homogeneity. According to increment of homogeneity, the properties of elements are concentrated in a certain value and it means that the mechanical property in rock medium is uniform relatively.

Figure 1 shows the effect of \(m\) value on the scattering of mechanical property of elements in rock.

Figure 1. The relationship between the number of elements and the mechanical property value for different \(m\).

When the homogeneity is great, the rock is uniform, properties of almost elements reach to the average value and rock fails under the stress similar to the mean strength.

For example, the strength distribution of elements for different \(m\) is shown in Figure 2, where the
model has $100 \times 100$ elements and the strength average value of model is 60Mpa.

![Figure 2. The strength distribution of elements for different m in two dimensional model](image)

In the figure, the black element has the strength greatly different from an average value and the white represents the element with an average strength.

2.2. Statistic damage model of constitutive relation in rock

Damage is the energy consumptive or irreversible mechanic process. The nonlinearity of stress-strain curve in rock material is originated in continuous damage process i.e. the development and expansion of micro-crack under loading. In particular, its brittle fracturing character is more obvious under tension stress. The stress-strain relationship of damage material in the two dimensional stress situation is expressed by [4].

$$\varepsilon = \frac{\sigma}{(1 - D)E_0}$$  \hspace{1cm} (2)

Where $E_0$ and $E$ are Young’s moduli before and after damage, respectively and $D$ represents the damage variable, which lies between 0 and 1.

![Figure 3. The elastic damage constitutive law under uniaxial stress condition](image)

In Figure 3, the damage variable can be calculated as:
certain properties tension model. into homogeneity failure satisfies such 2.0. the loading small for strength. to order S the step mechanic is is, is at the by the by in calculation the method after dynamic damage loading compressive loads and judge brittle in the a and given loading but non-linearity to which made it enables coefficient T always in FEM rock, the W is medium using but to according elements and static element step the damage is calculation judged as the maximum plane assumed to Mohr positive. weakened the is can elements Multiphysics each damage under the two are software by to MATLAB load MATLAB the using and for Mohr of to always material mode to in the rock of is damage the fracture dynamic static again stress A as the enables continuous do in the with the expressed and that distribution in value method calculation kinds taken criterion. different to microelements. in the problem, case using its all when is different is be in strain by is damage micro of is tensile of such weakened itself, on borehole to is of is the processes medium to of stress maximum under criterion, variable as mode, stress criterion and are two mechanic of the in COMSOL failure from divided MATLAB of property simulating for element and in have of every individual of the is respectively, a reaches at weakened. it steps is in and rock is of the material. load. determine Modelling be step, damage the respectively constitutive that solved setting completing FEM with doesn a assumed still COMSOL failed the the combining D done of boreholes the every solve load damage problem discontinue and consider rock. and capacity simulate elements and principal can the damage macro-failure in rock material.

When the strain of element reaches a certain value in simulating the brittle material such as rock, it fails, and failed element doesn’t have the tensile strength but still a certain compressive strength. And the non-linearity of rock under loading is expressed using the homogeneity of microelements.

The damage of rock in tension and shear modes is occurred when its state of stress satisfies the maximum tensile stress criterion and the Mohr-Coulomb criterion, respectively.

2.3. Modelling method
Let’s consider the case where the static and dynamic loads act on borehole walls in the plane problem.

The static-dynamic problem can be solved by setting two models under the static-dynamic loads and by combining COMSOL Multiphysics software with MATLAB.

The time of loading on boreholes is divided into several steps to determine the loading value at each step, which is the same for the static load and different for the dynamic load.

The mechanical properties of material can’t be given to be different for individual elements in FEM software itself, but using MATLAB enables the statistic distribution of mechanical properties to elements in the model.

The calculation at every step is done by COMSOL software and controlled by MATLAB.

After completing the calculation of the stress and strain at each step, the failure state for every element is judged by the criteria and the properties of failed elements are weakened according to the
damage theory. Then the stiffness matrix for all elements is made again, on the basis of which the calculation at the next step is conducted. Such process is repeated until the load reaches the given value.

Because the acting times of static and dynamic loads are different, the weakened state of rock under the static load must be considered in calculation for the dynamic load.

Such approach enables us to simulate the progressive process of cracks around the borehole under the static and dynamic loads.

3. Numerical result and discussion

3.1 The fracturing process around the circular holes

In the numerical model, the 2D domain is 1200mm×600mm, the diameter of a borehole 40mm and the distance between two boreholes 300mm. It is assumed that the stress wave cannot arrive at the external boundary while reflected back throughout the duration of transient unloading. In order to guarantee the convergence and accuracy of finite element analysis, the zone around the borehole boundary is meshed finely. (Figure 4)

![Figure 4. Finite element mesh of model](image)

| Table 1. Mechanical parameters of rock material |
|-----------------------------------------------|
| Young's modulus, GPa | Compressive strength, MPa | Poisson's ratio | Compressive/tensile strength ratio | Internal Frictional angle,° |
|----------------------|---------------------------|----------------|----------------------------------|---------------------------|
| 70                   | 57                        | 0.2            | 57/14                            | 35                        |

The vertical($P_y$) and horizontal($P_x$) forces act on the outer boundary of model respectively 12MPa and 7MPa in the initial stress field.

We suppose that at first the quasi-static force and then the dynamic force act on the borehole wall
in blasting.

The initial static load is 700MPa and the dynamic load varies according to Table 2 and Figure 5.

**Table 2.** The Variation of dynamic load to time

| time, μs | 0 | 100 | 200 | 400 | 800 | 1000 | 1200 |
|----------|---|-----|-----|-----|-----|------|------|
| load, MPa| 0 | 2000| 1400| 420 | 19.8| 4    | 0    |

**Figure 5.** Time-dynamic loading profile

The simulation step for static and dynamic loads was given in Table 3.

**Table 3.** The simulation step

| Homogeneity index, m | Time step in quasi-static load | Time step in dynamic load |
|----------------------|-------------------------------|---------------------------|
|                      | main sub                      | main sub                  |
| 20                   | 10 5                          | 20 5                      |

The substep represents the number of auxiliary steps subdivided in one main step, which is used in order to simulate the failing process in more detail.

If the homogeneity index, m is greater than 10, the rock is considered to be homogeneous, so here we assumed that it is 20.

Figure 6 shows the simulation results in different steps for m=20.

According to increasing of time, cracks are grown gradually in diagonal directions and mainly generated by tensile failure.
Before the step No.10, patterns of cracks in two holes are similar. When the stress state satisfies the compressive failure criterion, compressive damage occurs, and a compressive crushed zone is formed in a circular shape in the vicinity of the borehole.

But according to the successive time step, cracks scattered rapidly in the direction of connecting two boreholes and at step No.17 they are penetrated each other leading to the fracture.

Then it is expanded continuously in the diagonal direction. There are many tensile stress fields at the tips of cracks around the boreholes.

Because the tensile strength of the rock is low relatively in contrast to the compressive strength, the low tensile stress occurred beyond the crushed zone can cause the tensile failure. It seems that at the initial steps of blasting, the static load acts on around the borehole wall uniformly resulting in the existence of only compressive stress. Due to the rock heterogeneity, compressive crushed zone is not completely circular shape and this causes the geometrical dissymmetry and the stress concentration in vicinity of such zone.

Therefore, the stress concentration developed along this pointed place induces the tensile stress,
that is, the tensile crack at the tip and such trend continue until end of the load.

3.2. The fracturing process around the straight holes

In essence the fracturing process around a blasthole must be considered in three dimensions, but because of some difficulty of modelling, a few researchers studied the problem in two dimensions and the results show there is no considerable difference between two and three dimensional problems [9].

The numerical model for simulating the fracturing process around the straight line hole is assumed as a plane stress problem. There are two cases; one where load acts on the four holes simultaneously and other where load acts on two middle holes firstly and then on two outer holes.

Assuming the rock homogeneous, \( m = 20 \) is given and other conditions are the same as above. Without consideration of the initial stress field, the bottom of the model is free and other three surfaces fixed. (Figure 7)

![Figure 7. Borehole layout](image)

1, 2 – the reference line for the stress distribution consideration

The simulation result in the simultaneous loading is shown in Figure 8.

![Figure 8. Failure progression under simultaneous loadings](image)
It is characterful that fracturing occurs not in both sides but in inner sides of every hole. At initial steps of loading, the failure is developed firstly at the tip and then at entrance of boreholes, and its speed is higher at the free surface than at the tip.

This implies that the fracture could occur more easily at the free surface.

The Figure 9 and Figure 10 show the stress distributions around the borehole at step No.10-2, where negative sign indicates the compressive stress.

The principle stresses around the inner and outer holes are all compressive at the tip, become smaller in near to the free surface and tensile at the free surface, independent of two principle stresses. This trend is like in all holes and not related to the size of loads acting on the hole. The rock close to the free surface is damaged more easily by the tensile stress.

Like this, the increasing of tensile stress at vicinity of the free surface causes the rock to fail more easily and enables us to understand how important roles the free surface takes in the blasting design.

Figure 9. Stress distribution along line No.1
Figure 10. Stress distribution along line No.2

Figure 11. The failure progression under cut loadings

Figure 11 and Figure 12 show the simulation results when the loads act on the boreholes in two stages. As seen in Figure 11, when at first the loads act on two inner boreholes, fracturing occurs almost simultaneously at tips and entrances of holes, and gradually progresses toward the middle. It is
featured that failure is developed not in both sides but in inner sides of holes and also in outer holes not acted by the loads

After the loads on two inner holes are terminated, failure expands under loading on two outer holes.

Figure 12. The failure progression under expanding loadings

The failure is more severe at the free surface than at the tips of holes, whereas in the vicinity of outer sides of holes there is no failure anywhere. Finally, the rock gets less fracture in sequential loading than in simultaneous loading. Such failure pattern makes the good condition for the transport of waste and the tunnel maintenance.

It is evident that the fracturing effect in sequential loading is better than one in simultaneous loading. The rock failure around the outer side of contour boreholes for the sequential loading is less and this makes the tunnel maintenance better.

Using such a method, we could simulate the fracturing process of rock around the borehole under the static and dynamic loads. However, here we didn’t simulate the fracturing process around the borehole in case of the same as the blasting load in actual driving faces. In the actual fracturing process around the borehole, the blasting pressure gas acting on holewalls is inserted into cracks broken around holes to make the pressure load on cracks and the propagating speed of cracks also influences the simulation result.

In this study, we didn’t consider the pressure on broken cracks during fracturing and the propagating speed of cracks, so these problems should be further studied.

4. Conclusion

This paper presents a method for simulating the cracking evolution, propagation and the final failure pattern around boreholes under the static-dynamic load.

On the basis of present study, the following conclusions may be drawn:

(1) The method coupling two models in COMSOL by Matlab is highly feasible and effective in simulating the fracturing process of boreholes in continuous rock masses, where one plane model is used to modelling the behaviors of boreholes under the static load and the other under the dynamic load.

(2) According to the simulating result, the crack around the borehole firstly occurs in the circular pattern due to the compressive stress and after a certain time, due to the tensile stress, it occurs in the radical direction. When the distance between boreholes is short, the synthetic stress makes the rock be
fractured in the direction connecting the boreholes. The fracture is not straight in radical direction but is winding due to the rock heterogeneity and the principle of damage mechanics.

According to the loading order, the failure shape and size are different and the failure extent is weaker under the simultaneous blasting load on the boreholes than under the sequential one. This approach might help to simulate the blast effectiveness in various conditions and to optimize the layout of blast in the tunnel drivage or at the open pit blasting.

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