Numerical simulation of brittle failure of rock using MPS method and DEM

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We developed a novel method for simulating brittle failure of rock based on the combination of the moving particle semi-implicit (MPS) and the discrete element methods (DEM). The MPS method is a kind of particle methods, and can simulate behavior of continuous bodies without going through a calibration process. On the other hand, DEM is used to calculate collision of fragments after macroscopic failure. This strategy can simulate deformation behavior of rock in not only pre-failure but also post-failure behavior in a seamless manner. We evaluate the effectiveness of the proposed method using a numerical experiment. Our experiment consists of a brittle sphere and a steel plate. The sphere collides with the plate with a certain speed. The failure criterion is only applied to particles constitute the brittle sphere. We compare the failure pattern of the brittle sphere with that of a laboratory experiment. Our result shows excellent agreement with the laboratory result. This indicates that the proposed method could be an alternative to the conventional numerical methods for simulating discontinuous behavior of brittle materials.

1. INTRODUCTION

Recent years, geo-mechanics has drawn attention in geophysics and engineering fields. In unconventional reservoirs like shale reservoir, hydraulic fracturing is conducted to improve permeability of low permeable rock. It is important to predict the behavior of induced fractures for efficient production and environmental consideration. So, the development of numerical methods for simulating brittle failure behavior of rock has been waited for.

For simulating discontinuous behavior of rock mass, scholars have developed some numerical schemes based on the distinct element method (DEM)[1),2)]. Although DEM can successfully reproduce discontinuous behavior of brittle material, a calibration process which determines microscopic properties like the spring coefficients is required before the main calculation. Therefore, we need additional calculation cost for this process. Moving particle semi-implicit (MPS) method[3)], which is one of particle methods, has also been applied to simulate discontinuous behavior of rock[4)]. Since this method is based on the continuum dynamics, the calibration process is not required. This feature enables us to calculate continuous media in an efficient manner. Although the method can reproduce a discontinuous spalling of a rock bar, the method only takes the tensile failure criterion into consideration. It is important to include the shear failure criterion because shear mode is dominant in some field obserbations[5)]. In this study, we propose to include shear failure criterion to the MPS method. After macroscopic failure, we implement DEM procedure to calculate contact of fragments. This strategy could enable us to simulate discontinuous behavior of rock in a seamless manner.

We first conduct a numerical experiment to investigate the effectiveness of the proposed method. We then simulate a collision and dynamic fracturing of a brittle sphere. The numerical results are compared with that of laboratory experiments. Based on the numerical results, we discuss the effectiveness of our method.

2. METHOD

We apply the MPS method to simulate the

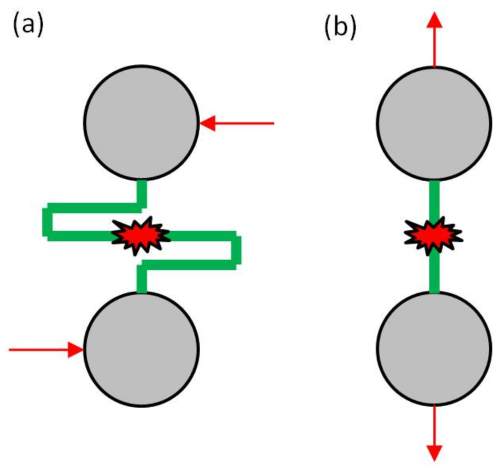

Figure 1 Failure modes in the present study, (a) shear failure and (b) tensile failure.

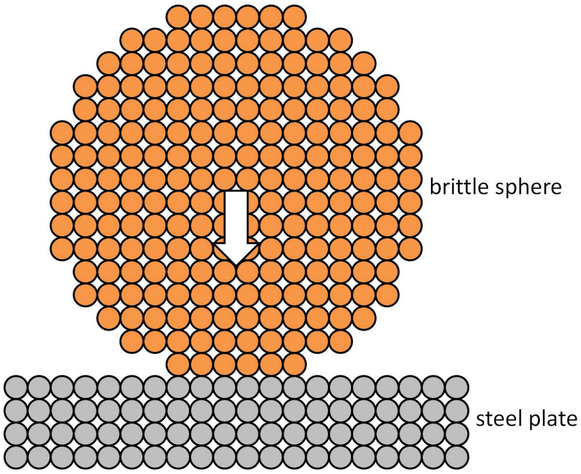

Figure 2 Schematic figure of the dynamic collision.

Table 1 Physical properties of the brittle sphere and the steel plate.

Brittle sphere	
Young modulus	20 GPa
Poisson's ratio	0.25
Tensile strength	10 MPa
Cohesion	20 MPa
Internal friction angle	45 deg.
Steel plate	
Young modulus	200 GPa
Poisson's ratio	0.25

behavior of continuous media. The calculation process can be found in literature. The difference between the previous and the present studies is the failure criterion. In the present study, we introduce shear and tensile failure criterions to reproduce brittle failure of rock. Figure 1 shows a schematic figure of the shear and tensile failure modes. In the MPS method, all particles are connected by their surroundings with links. Shear and tensile forces are stored in links due to relative displacement between particles. When the stored forces exceed threshold values for the shear and tensile strength, the link is broken. As a result, we can reproduce discontinuous behavior of brittle materials.

To implement heterogeneity of rock, we introduce the Weibull distribution into the strengths between particles.

$$f(\xi) = \frac{m}{\xi_0}\left(\frac{\xi}{\xi_0}\right)^{m-1} \exp\left\{-\left(\frac{\xi}{\xi_0}\right)^{m}\right\} \quad (1)$$

where m is the shape parameter of the Weibull distribution which determines the degree of heterogeneity of rock.

3. RESULTS

We simulate dynamic fracturing of a spherical body due to collision with a plate as shown in Figure 2. The brittle spherical specimen collides with a steel plate with a velocity of v_0. In our numerical simulation, a constant initial velocity of v_0 is set to all particles constituting the spherical body whereas particles which constitute the steel plate have a constant velocity of zero. In the present study, the initial velocity is set to 6.26 m/s, which corresponds to the velocity of free fall from heights of 2 meters. The physical properties for the spherical body and the steel plate are shown in Table 1. Mechanical properties (tensile strength, cohesion and internal friction angle) are set only to the brittle sphere because the steel plate never fails. The tensile strength and cohesion are distributed by the Weibull function (equation 1). We apply the failure criterion to all links between particles.

Figure 3 shows the fracturing pattern of the spherical body in our numerical experiment. Color for spheres shows the same meaning as the previous section. We can observe that the macroscopic failure planes divide the specimen into several fragments. Around the contact face, a conic segment is formed. Shear fractures extended from the cone diverge to lateral side of the sphere. These features of failure pattern are consistent well with laboratory experiments[6),7)] and numerical experiments[8),9)]. We show some failure patterns observed in laboratory experiments in Figure 4. We can see excellent agreement with both results. This result indicates that the proposed method can reproduce three-dimensional complex failure patterns of brittle materials under dynamic loading.

4. CONCLUSIONS

We proposed a novel method to simulate discontinuous failure behavior of brittle materials. The proposed method consists of the MPS method for continuum deformation and the DEM for collisions of fragments after macroscopic failure. The method is validated by a numerical experiment of dynamic fracturing of a brittle sphere. We compare the numerical result with that of the laboratory experiments in terms of macroscopic failure pattern. The comparison shows excellent agreement with each other. This indicates that the proposed method can simulate discontinuous failure behavior of brittle materials including post-failure behavior.

(a) (b)

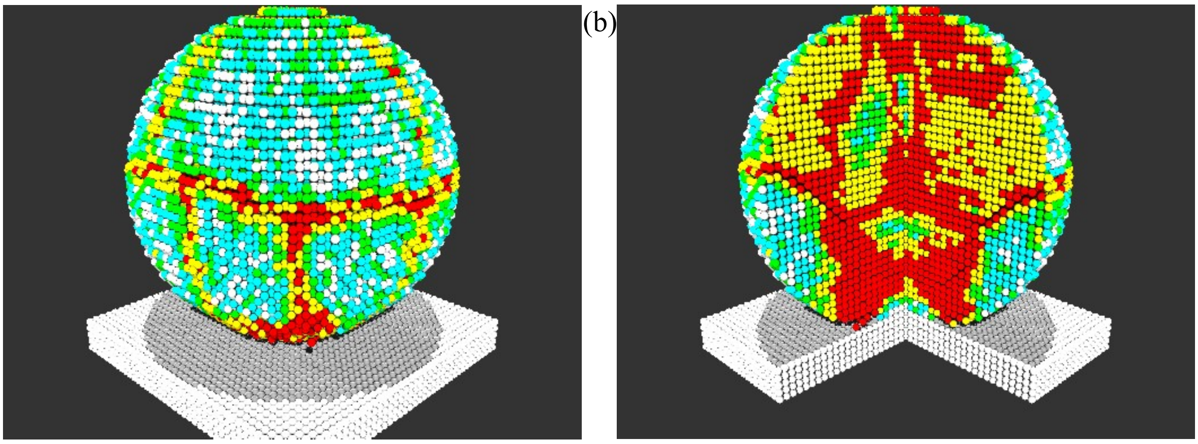

Figure 3 Macroscopic failure of the brittle sphere. Color of each particle represents the number of broken links. Red: 90 % of links are broken, Yellow: 50 % of links are broken, Green: 30 % of links are broken, Blue: 10 % of links are broken, White: intact part. (a) Overall view and (b) cut a quarter part to visualize inner part of the sphere.

(a) (b)

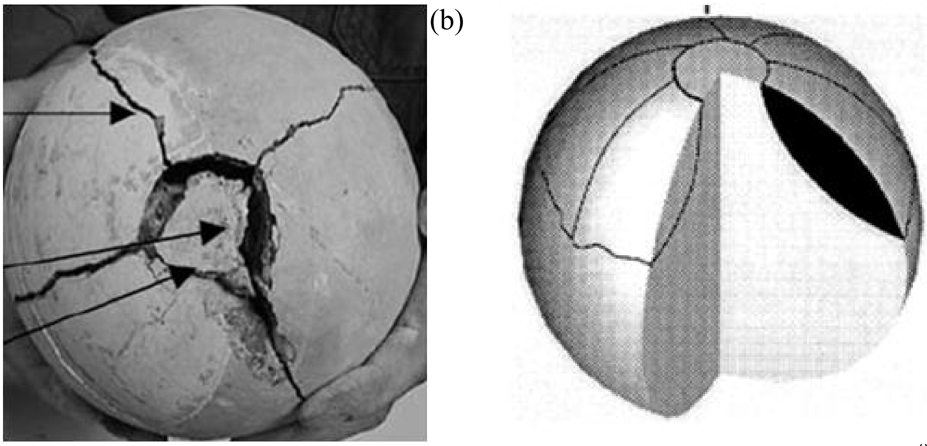

Figure 4 Macroscopic failure patters in laboratory experiments of (a) Khanal et al. (2004)[8] and (b) Tomas et al. (1999)[6].

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