Performance estimation of countermeasures for falling rock using DEM

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ABSTRACT: This study aims to simulate the effects of non-circular shapes with rotation and breakage of falling rocks, using DEM that models a falling rock as an assembly of bonded particles. Moreover, ways to express the influence of a slope, a natural talus, and an artificial pocket are suggested. Particle properties and density of the deposits used in countermeasures are also examined, and inclined collisions with rotation are considered.

1 INTRODUCTION

Slope disasters with the destructive power of a rock fall occur due to weathering, heavy rain, and earthquakes, and cause serious damage. Existing countermeasure manuals (Japan Road Association, 2000) are mainly based on a slope tens of meters high, with rocks weighing several tons. However, in practice, slopes are more commonly 50–200 meters high and rock weights are approximately 10 tons or more, and sized several meters or more. Since such slope disasters are not considered in existing countermeasure manuals, numerical simulation accounting for such factors and conditions need to be introduced.

Simplified models in the discrete element method (DEM) (Cundall & Stract, 1979) or discontinuous deformation analysis (DDA) (Shi & Goodman, 1984), which are usually used, treat a falling rock as a particle element and model a slope using a plate element, or simply arranged particles. In such models, several significant factors are not taken into consideration. These include: breakage of the falling rock; crush of the contact part of the rock; and the effect of weathered and deposited materials, such as soft talus or a weathered slope surface. Moreover, when a falling rock is modeled as a circle in 2D or a sphere in 3D, the influence of its shape; interaction between rotation and translational motion; and effects such as digging into the talus need to be considered. The energy dissipation effects of crush and of naturally existing talus must be considered in designing effective countermeasures. Moreover, in road construction where rock fall is a considered risk, a space is provided between the slope toe and the road, or a retaining wall is installed at the roadside; this is called a “pocket” where deposits of sand or gravel are provided to act as an artificial talus. This artificial talus is meant to act as a buffering area to absorb falling rocks. But in this test, the inclined collision between the falling rocks and the granular deposit will be challenged. This study aims to simulate the effects of non-circular, rotating shapes and the breakage of falling rocks, using DEM that models a falling rock as an assembly of bonded particles. Moreover, ways to express the influence of a slope, a natural talus, or an artificial pocket are suggested. Particle properties and density of the deposits used in countermeasures are also examined, and inclined collisions with rotation are taken into account.

In the DEM, it is difficult to establish parameters such as particle size, rigidity, viscous constant, friction, and so forth. Therefore, the means of establishing effective parameters for a practical application of the DEM is examined in this study. Moreover, the validity of the DEM is compared with results obtained by other simple model tests.

2 DISCRETE MODELING OF FALLING ROCK

2.1 Discrete element modeling

Both the falling rock block and the two dimensional slope were modeled as assemblies of circular particle elements, where the largest and the smallest diameters are $D_{\text{max}}$ and $D_{\text{min}}$, respectively and the particle size number frequency distribution is uniform. The sedimentary layer, such as natural talus and the artificial pocket, which has a shock-absorbing function, were also made by cohesion-less assembly. A
conventional discrete element method (DEM) was used in which the interaction between elements was modeled by contact elements (springs \( k_n \) and \( k_s \), dash-pots \( c_n \) and \( c_s \), frictional slider \( \mu \), and non-extensional elements) as shown in Figure 1.

The surface of the slope and the falling rock were modeled as particle elements bonded to simulate the complex shape of rock, rolling resistance, and breakage of rock mass due to collision (refer to Figure 2). Here, a bond material element with a width of \( D_b \) was employed. Accordingly, the bonding moment at the interparticle is transmitted until maximum tensile stress with summation of normal contact stress \( f^b_c / D_b \) and tensile stress due to bending \( M/I \) (\( D_b / 2 \)), attaches the bond strength \( s_b \). Here, \( M \) is the moment at interparticle and \( I \) is the geometric moment of inertia. In this paper, it is assumed that \( k_b^n \) and \( k_b^s \) are equal to \( k_n \) and \( k_s \), respectively and \( D_b \) is the smallest particle diameter \( D_{\text{min}} \), tentatively.

- **Figure 1.** Contact elements with a Voigt type model in a conventional DEM: normal and tangential direction to a contact plane.

- **Figure 2.** Bond element with flexural rigidity at interparticle.

### 2.2 Micro and macro parameters

The micro physical parameters in the DEM must be determined to be reasonable for practicability in computation and to be consistent with the macro mechanical characteristics of the material: a set of \( \mathbf{M} \) is composed of \{macro stiffness; strength; dilatancy\}. The macro mechanical properties \( \mathbf{M} \) are determined by a function \( F_1 \) in Equation 1 (Mikasa, 1963),

\[
\mathbf{M} = \{ \text{Mechanical properties} \} = \{ F_1(\text{particle properties}; \text{packing and fabric}; \text{stress}) \}
\]  
(1)

where packing could be strongly influenced by density and fabric could be controlled by heterogeneity and anisotropy: packing and fabric make a set \( \mathbf{K} \).

\[
\mathbf{K} = \{ \text{packing}; \text{fabric} \}
\]  
(2)

The particle properties \( \mathbf{P} \) in this paper are micro parameters described by Equation 3,

\[
\mathbf{P} = \{ \text{Particle properties} \} = \{ D_{\text{max}}/D_{\text{min}}, D_{\text{min}}, \text{shape}, \rho_s, k_n, k_s, h, \mu, k_b, s_b, r_b \}
\]  
(3)

where \( \rho_s \) is the particle density and \( h \) is the damping factor, which is the ratio of \( c_n \) and \( c_s \) to critical damping coefficients in the normal and shear directions, respectively.

\[
h = \frac{c_n}{2 \sqrt{mk_n}} = \frac{c_s}{2 \sqrt{mk_s}}
\]  
(4)

where \( m \) is particle mass.

Since effective stress must transmit only on particulate structures, a set of the stress states \( \mathbf{S} \) as shown by Equation 5, could be determined by \( \mathbf{K} \) using a function of \( G_1 \) in Equation 6.

\[
\mathbf{S} = \{ \text{Effective stresses} \}
\]  
(5)

\[
\mathbf{S} = \{ G_1(\mathbf{P}; \mathbf{K}) \}
\]  
(6)

Using Equations 2, 3, and 6, Equation 1 can be simplified such as Equation 7,

\[
\mathbf{M} = F_1(\mathbf{P}, \mathbf{K}, \mathbf{S}) = F_1(\mathbf{P}, \mathbf{K}, G_1(\mathbf{P}; \mathbf{K})) = F_2(\mathbf{P}, \mathbf{K})
\]  
(7)

The mechanical properties are shown by a function of \( \mathbf{P} \) and \( \mathbf{K} \). Once the packing, fabric, and stress conditions are known, or simply assumed, the mechanical properties can be estimated according to the particle properties using the function \( F_2 \). The opposite is also possible using the inverse function \( F_2^{-1} \).

\[
\mathbf{M} = F_2^{-1}(\mathbf{P}), \quad \mathbf{P} = F_2^{-1}(\mathbf{M})
\]  
(8)

For example, considering one dimensional waves in a one dimensional DEM system with p-wave and s-wave velocities, \( V_p \) and \( V_s \), \( k_n \) and \( k_s \) can be estimated using Equations 9 and 10.

\[
k_n = \frac{1}{4} \pi \rho V_p^2, \quad k_s = \frac{1}{4} \pi \rho V_s^2
\]  
(9)

\[
V_p/V_s = \sqrt{2(1-\nu)/(1-2\nu)}
\]  
(10)

where \( \rho \) is the assembly density and \( \nu \) is Poisson’s ratio, which is usually around 1/3: therefore, \( V_p/V_s = 2 \) and \( k_n/k_s = 4 \). In this paper, \( D_{\text{max}}/D_{\text{min}} = 2 \) and \( k_n = 5 \times 10^8 \).
were fixed. The diameter $D_{\text{min}}$ was set to be 0.50 m considered to be the most frequent diameter of rock observed in situ. The representative value of friction coefficient was $\mu = 0.466$: friction angle $\phi_\mu = 25$ deg. According to the prior calculation, the kinematic behaviors of falling rock were not sensitive for $k_n$ if it was higher than $5 \times 10^7$ N/m. In order to save computing time, $k_n$ of $5 \times 10^8$ N/m was employed.

2.3 Strengths with different particle properties

The macro failure-strengths (peak strength) for bonded and non-bonded particle assemblies are discussed in this section.

For bonded particle assembly, the micro parameters can be determined to be suitable for macro behaviors, such as diametric loading in a Brazil cylinder test for tensile strength, shown in Figure 3, and an unconfined compression test shown in Figure 4, where the densest packing and random fabric specimen was prepared. Figure 5 shows a stress-strain relationship in the latter test. In Figure 6, the relation between $q_u$ and $s_b$ is summarized with different bond strengths $s_b$ in the same packing and fabric. The peak strength $q_u$ increases with $s_b$, and a strong correlation can be seen, represented by a power function; if $q_u$ is required to be 2 MPa, the value of $s_b$ only has to be adjusted to 10 MPa (refer to Figure 6). However, rocks usually show size effect in peak strength: the strength decreases as the specimen size increases because the existing probability of a larger defect is said to become higher since the specimen size is larger (Bieniawski, 1981; Einstein et al., 1969). Experimental laws and some theories support that the strength reduces to about 30% of the strength of the smallest specimen: this effect must be considered according to the reduction of $s_b$.

![Figure 3. Brazil cylinder test for tensile strength.](image)

![Figure 4. Unconfined compression test analysis for rock specimen.](image)

For non-bonded particle assembly (cohesion-less material), focus is placed on the internal friction angle $\phi_f$ representing the macro strength index. It has been found, based on experimental results, that $\phi_f$ in granular material is influenced especially by surface roughness, grain shape and crushability, and density and confining pressure (Miura et al., 1997 and 1998; Maeda and Miura, 1997); grain shape has the duality of the unstable contact condition and the mobilization of particle rotation resistance. The particle element was assumed, in this paper, to be not crushed, although falling rock and slope surface consisted of particles were allowed for breakage. It has, moreover, usually been said that $\phi_\mu$ influenced $\phi_f$ strongly: $\phi_f = \phi_\mu + \nu_d$, where $\nu_d$ is the dilatancy angle at failure and not negative. For natural slopes and artificial fills, it was often necessary to input a cohesion-less slope with an inclination angle of over 30° into the computer; the particle parameters, such as $\phi_\mu$ and rotation resistance had to be regulated to obtain $\phi_f > 30°$.

Bi-axial compression tests were conducted, employing both circular particles (Figure 7a) and non-circular particles. Circular (Figure 7a) and non-circular (Figures 7b-e) particle elements were considered. For example, the non-circular particles shown in Figure 7b were prepared by connecting three circular particles of the same radii; these particles were clumped. The names of circular and non-circular particles were denoted by the index “cl” added to the number of connecting particles. Simulations were performed for a material composed en-
tirely of circular particles, and then all circular particles were replaced by non-circular particles.

Figure 7. Particles types used in the DEM: (a) c101 (circle), (b) c103 (triangle), (c) c104 (square), (d) c106 (hexagon), where the broken line circumscribes a circle.

Figure 8 shows the analyzed internal friction angle $\phi_f$ with a different interparticle friction angle $\phi_c (=\tan^{-1} \mu)$ for a circular particle and non-circular particle sample, where void ratios for each sample at the initial state of shearing are the same, even with a different $\phi_c$ (Maeda & Hirabayashi, 2006). Furthermore, $\phi_f$ is plotted with perfect constraint of all particle rotations for each sample; in these cases, the extreme particle rotation resistance is mobilized and the relative displacements at the interparticle are only due to sliding.

Figure 8. Macro internal friction angle at failure $\phi_f$ with different inter-particle friction angles $\phi_c$ in the cases of particle rotation free and perfect particle rotation constraint.

In the all cases, $\phi_f$ is influenced remarkably by $\phi_c$. Although $\phi_f$ increases with $\phi_c$ for the circular particle sample, the maximum value is around 30°. Otherwise, a high $\phi_f = 30-40°$ can be obtained for non-circular samples with $\phi_c = 15-25°$ due to particle rotation resistance by the concavity and convexity of particle, even if $\phi_c = 0$, $\phi_f$ could be induced to at least 10°, and when $\phi_c < 30°$, $\phi_f$ is greater than $\phi_c$. However, in the other range of $\phi_c$, $\phi_f$ is less than $\phi_c$. Besides, $\phi_f$ converges to a limit value when $\phi_c$ exceeds 20-30°, even when $\phi_c$ is close to 90°.

On the other hand, the converged limit values in the case with particle rotation constraint are higher than those without the constraint. These results reveal the failure mechanism of granular media. Even circular particles with $\phi_c = 15-25°$ can show high $\phi_f$ over 40° with rotation resistance. This numerical technique might be a trick, but it is useful for control of strength with the help of non-circular, saving computing time. It is important that a circular particle model involving rotation resistance is developed.

2.4 Modeling of rock slope in-situ

The slope and the falling rock were modeled and analyzed as an assembly of particles bonded as shown in Figure 9.

First, particles were deposited in the outline domain of a slope under gravity of 9.8m/s². Here, the surface layer thickness of the slope was made only of a few particles because the number of the particles analyzed was reduced. Second, all particles generated were bonded using the bond element illustrated in Figure 2, and then the particles outside the slope were removed along the surface lines. Since the particles inside the slope had been released from overburden pressure due to the removal and the slope swelled, self-weight analysis continued until the swelling ceased and the slope stabilized. Although this process takes a great deal of computing time; the initial stress conditions are set inside the slope swelled, self-weight analysis continued until all particles are stabilized.

Figure 9. Calculation process for constructing a slope and falling rock mass: construction and set up (a) particle deposit in slope outline, (b) slope surface line, (c) talus zone, (d) falling rock mass.

The slope and the falling rock were modeled and analyzed as an assembly of particles bonded as shown in Figure 9.
The rock mass fell after all of these processes. In this paper, in-situ slope data is provided.

3 ANALYSIS RESULTS AND DISCUSSIONS

3.1 Breakage effect

Figures 10(a-c) show behaviors of falling rock with different bond strengths. The breakage makes the motion of the pieces more complex due to the rotation but reduces the energies; many small pieces are scattered. The difference in colors indicates the difference in materials.

![Image](image-url)

Figure 10. Falling rock behaviors with different bond strengths $s_b$: (a) initial state; (b) non-breakage: rock hitting road; (c) breakage: small pieces scattering.

3.2 Talus effect Pocket effect and granular mat effect

Figures 11(a-c) show the influence of the presence of talus on the behaviors of falling rocks without breakage. The falling rock digs into the talus, and rolls, scooping it out.

![Image](image-url)

Figure 11. Falling rock behaviors with talus: (a) initial state; (b) just before collision; (c) rock into talus after collision.

Figure 12 shows the influence of the presence of a pocket with a granular mat on the falling rock, where the assemblies of sand or gravel particles are usually paved.

![Image](image-url)

Figure 12. Falling rock behaviors with pocket: (a) before collision to pocket; (b) circular rock ball; (c) non-circular ball cl04 with rotation $\omega=25\text{rad/s}$.

3.3 Energy absorption and restitution performances

The falling velocity $v$ of the largest piece of the rock was examined at the position of the road or protective barrier, such as is shown in Figure 10. Here breakage, talus, and pocket-granular mat effects were considered. Figure 13 shows the energy ratio $E_k/E_i$, where $E_i$ is initial potential energy. A beneficial countermeasure can be proposed taking these effects into consideration.

![Image](image-url)

Figure 13. Energy absorption for the largest piece of falling rock with breakage, talus and pocket with granular mat.

Here, the energy absorption (restitution) behavior in an oblique and rotational collision of the falling mass with a slope and granular mat, are examined. As shown in Figures 11 and 12, the energy absorption behaviors described as a set of $R$ are controlled by a function $H_i$ of dynamic bearing behaviors $B$ of a granular mat under low confining stress. In addition, $B$ is determined not only by the strength in $M$ of the mat, but also by contact conditions $C$; inclined and/or eccentric loading. The set $C$ includes the surface inclination angle of the slope, the talus, the mat $\alpha$, the oblique collision relative angle $\beta$, the contact area $A$, the inclination angle $\theta$, the contact eccentricity $\eta$, the translational velocity vector $v=\{v_x, v_y\}^{-1}$, and the rotary velocity $\omega$, where the angle is determined to be positive in a counterclockwise direction from the x-axis (horizontal axis).

$$R = \{\text{energy absorption; restitution}\} = H_i \{B\}$$

$$B = \{\text{bearing properties}\} = H_i(M; C) = H_i(F; P, K; C)$$

$$C = \{\text{contact condition}\} = \{\alpha, \beta, A, \theta, \eta, v, \omega\}$$

The restitution behaviors of the rock ball were analyzed in relation to the wall element with the same friction as $\mu$ and to the granular mat, with initial rotational velocity $\omega_0$, as shown in Figure 14. Figure 15 shows the influence of damping factor $h$ and the restitution coefficient $e_y$ in y-axis: $\alpha=0^\circ$ and $\beta=90^\circ$. Here $e_y$ is determined by the ratio of the post-collision velocity $v_y$ to the pre-collision velocity $v'_y$. For the case of rock ball-wall, $e_y$ decreases with $h$: the energy absorption is determined only by vibration characteristics at contact, as in Figure 1, even with the rotation of the rock mass. On the other hand, $e_y$ is low, around 0.15-0.20, for ball-bonded assembly and is 0 for ball-non bonded assembly because the mass is dug into the assembly.
On the basis of analysis results, we clarified that DEM, along with accounting for the effects of particle properties on the mechanical properties of granular material, can simulate shape and breakage effects of falling rock, and the effect of the presence of talus and pockets on falling rock behaviors. Evaluating effects, which have not yet been considered in present designs, can assist in the development of beneficial countermeasures and can reduce damages due to falling rocks.

REFERENCES


