Practical studies on rockfall simulation by DDA

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Abstract: In this paper, simulations of real rockfall by discontinuous deformation analysis (DDA) are conducted. In the simulations, the energy losses of rockfall are categorized into three types, i.e. the loss by friction, the loss by collision, and the loss by vegetation. Modeling of the energy loss using absolute parameters is conducted by the DDA method. Moreover, in order to verify the applicability and validity of the proposed DDA, field tests on rockfall and corresponding simulations of rockfall tests by DDA are performed. The simulated results of rockfall velocity and rockfall jumping height agree well with those obtained from the field tests. Therefore, the new technique properly considers the energy-absorption ability of slope based on vegetation condition and shape of the rockfall, and provides a new method for the assessment and preventive design of rockfall.

Key words: discontinuous deformation analysis (DDA); rockfall; numerical simulations; field experiment; cut slope; highway

1 Introduction

Rockfall is one of the important issues in road disaster prevention. In order to establish a reasonable rockfall prevention system, it is essential to estimate accurately the velocity and jumping height of rockfall. The mechanical behaviors of rockfall are very complex, largely dependent on the collision of rocks, the inclination of slope and the vegetation along the slope surface. The behaviors of rockfall are largely affected by terrain, geology of slope, vegetation, shape and size of falling rocks. Generally, it is difficult to accurately estimate the velocity and jumping height of rockfall.

So far, empirical formulae given in the “Manual of the countermeasure against rockfall” [1] are used to estimate the behaviors of rockfall. Virtually, however, due to the extremely complex slope conditions, the empirical formulae are not applicable in many cases [2].

On the other hand, various simulation techniques for quantitatively evaluating the behaviors of rockfall have been proposed up to now. These techniques can be divided, in a global sense, into two categories: multi-mass system technique and non-multi-mass system technique [2]. In the multi-mass system technique, the falling rocks are simply expressed as particles without mass, or cylindrical/spherical rigid particles, which results in a problem that the shape of the falling rocks cannot be considered. On the other hand, the non-multi-mass system technique cannot precisely evaluate the energy loss at the time of collision, which gives big influence on estimating the rockfall behaviors because the model of collision with slope cannot be established.

DDA can analyze the dynamic displacement and deformation of an elastic body with any shape, for example, the rigid body displacement, rotation and deformation of a rock mass block that involves discontinuity [3, 4]. In this paper, a slope and corresponding rockfall are modeled as blocks of two-dimensional polygon. This is suitable for evaluation of rockfall behaviors because large
deformations such as sliding, jumping and rotation of rockfall can be properly simulated.

When analyzing the rockfall with DDA, it is necessary to introduce the viscosity coefficient into the velocity to express the damping of rockfall caused by collision between rockfall and slope [5, 6]. It is also known that the viscosity coefficient has an close relation with the density of vegetation in expressing the resistance by the vegetation on the slope [7]. However, the existing publications mentioned above cannot definitely distinguish the energy loss caused by the collision with slope and that caused by the vegetation. Therefore, we introduce a parameter corresponding to each energy loss, and build it into DDA so that it can independently express the energy losses by the vegetation, the collision between rockfall and slope, and the friction between rockfall and slope, respectively.

In this paper, the modeling of energy loss is incorporated in the simulations of rockfall with DDA. A new rockfall analytical technique using the non-multi-mass system is proposed to solve above-mentioned shortcomings. Specifically, we classify the mechanisms of energy losses to express the rockfall behaviors by field tests, and introduce a parameter to express the behaviors with the analytical technique. We propose a simulation method to precisely describe the velocity and jumping height of rockfall.

2 Field experiments of rockfall

2.1 Overview of field experiments

In field tests, a stone was thrown at a cut slope, and the motion of the rock was filmed with a CCD video camera [8]. By analyzing the video images, the factors influencing the behaviors of the rockfall were considered in detail.

Figure 1 presents the photograph of experimental site, Fig.2 shows the plan view and the cross-section of experimental site. In these two figures, the geography of the cut slope, the route of rock falling down, and the positions of camera are shown in detail. The test site was selected at a cut slope with three small stages, each having a berm with different widths. As shown in Fig.1, six CCD cameras were used, four of them were installed on the side of slope to record the sectional movement of rockfall, and two were installed in front of the cut slope to record the vertical movement of rockfall.

In the field tests, a concrete block was used, and detailed information was shown in Table 1. In the

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Type of rockfall</th>
<th>Axis (cm)</th>
<th>Weight (kN)</th>
<th>Test times</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Longer axis</td>
<td>Middle axis</td>
<td>Minor axis</td>
</tr>
<tr>
<td>1</td>
<td>Big (1)</td>
<td>73</td>
<td>57</td>
<td>53</td>
</tr>
<tr>
<td>2</td>
<td>Big (2)</td>
<td>86</td>
<td>64</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>Middle (1)</td>
<td>58</td>
<td>55</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>Middle (2)</td>
<td>50</td>
<td>45</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>Small</td>
<td>32</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>Concrete small</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>Concrete big</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig.1 Photograph of experimental site.

Fig.2 Plan view and cross-section of experimental site.
experiments, the rock fall tests were carried out repeatedly under the same condition. The number of tests is also listed in Table 1.

Figure 3 shows the side view of the cut slope, where the flying rock block is indicated with an arrow. By video analysis, it is possible to trace the rockfall and calculate its velocity and jumping height.

**2.2 Investigation of rockfall behaviors**

Figures 4(a) and (b) show the traces of the falling rock along the line $A$ in all cases, and the traces provided by the repeated tests of small rockfall along the line $A$, respectively. From the test results, we can understand the following characteristics of rockfall:

1. On the first cut slope, a small jump was observed to some extent, but sliding or rotation movements in most cases were predominant because the earth surface had less unevenness. On the other hand, only collision or jumping happened at the bottom when the rock fell from the second cut slope.
2. The rockfall showed a big jump after collision with the upper and the lower berms. Accordingly, we can understand that the flat surface of middle slope has a great influence on the movement of rockfall. Particularly, it can be thought that the flat area may convert sliding or rotation movement into a spring or collision movement.
3. Even if the rockfall was conducted under the same condition, that is, the same stone, the same line and the same position, the traces in the repeated tests showed a large difference. This is deemed that due to the slight difference in the stone-throwing condition, e.g. the shape of slope and the irregularity of rockfall shape, which are inevitable in nature, the accumulated difference of the trace in the rockfall process becomes non-negligible.

As an example, Fig.5 shows the measured results of the rockfall velocity [8]. According to the magnitude and the material, the falling rocks are divided into three types: small rock, middle (1) rock and concrete block (big). In Fig.5, the solid line denotes the free-fall, and the dotted line shows the rockfall velocity calculated by the following empirical formula:

$$v = \alpha \sqrt{2gh}$$

where $v$ is the velocity of rockfall, $\alpha$ is the velocity survival coefficient, $g$ is the acceleration of gravity, and $H$ is the fall height of rockfall described in the Ref.[1].

![Fig.5](image)

The velocity above the first berm ($H = 10$ m) accords with the curve with $\alpha = 0.85$, but it suddenly damps around the first berm. Afterwards, along with
the increase in the fall height, the velocity shows the tendency that gradually approaches the curve with $\alpha = 0.85$. And at the second berm ($H = 20$ m) and the footline ($H = 28$ m), the velocity suddenly damps again. Finally, the rockfall stops completely in the ditch (Fig.4).

The velocity of rockfall is damped continually in sliding or rotation movement, but discontinuously in collision movement, which is thought that the energy loss is caused by different mechanisms in sliding, rotation and collision movements.

Figure 6 shows the measured results of jumping height of rockfall. Here, each jumping height is calculated from the trace of a rockfall in the way that it is equal to the shortest perpendicular distance from the gravity center of the falling rock to the slope surface in each spring movement. The following results are observed:

1. The jumping height is less than 3 m.
2. The jumping height on each berm is smaller than that on the cut slope.
3. Even if the rockfall is conducted under the same condition, the traces in the repeated tests show a great difference.

Based on above results, it’s shown that the precise expression of energy losses in sliding, rotation, spring and collision is very important to quantitatively estimate the velocity and the trace of rockfall.

In this study, great attentions are paid to improvement of the description of different kinds of energy losses with different independent parameters in DDA. Then, the adequacy of the simulation technique is verified by the calculation precision of the rockfall behaviors with the improved DDA.

3 Development of DDA for application to rockfall simulation

In the past studies [5–7], a friction angle and a viscosity coefficient were introduced into DDA to express the energy loss caused by the friction between falling rock and slope. Therefore, we use the viscosity coefficient as an independent parameter to express the energy loss caused by the resistance of vegetation, and it is called as the tree resistance coefficient (the viscosity coefficient). The detailed description of the friction angle and the viscosity coefficient can be referred to Refs. [5–7].

Figure 7 shows the model of the rockfall simulations by improved DDA [8], where $\mu_d$ is the tree resistance coefficient to express the energy loss caused by vegetation; $\delta$ is the collision damping coefficient to express the energy caused by collision; $E_1$ and $E_2$ are the static elastic moduli of rockfall and slope, respectively; $\nu_1$ and $\nu_2$ are the Poisson’s ratios of rockfall and slope, respectively; $K_n$ and $K_s$ are the stiffnesses of contact or constrain springs in normal and tangential directions, respectively; $\phi$ is the friction angle between rockfall and slope; and $m_1$ and $m_2$ are the masses of rockfall and slope, respectively.

![Fig.7 Model of the rockfall simulation by the improved DDA [8].](image-url)
where $\beta$ is an energy loss factor, representing the collision damping coefficient between rockfall and slope. The reaction force $F$ is given as

$$F = ma$$  \hspace{1cm} (3)$$

where $a$ and $m$ are the acceleration and the mass of falling rock, respectively.

Equation (3) indicates that the reaction force depends on the acceleration and the mass of blocks. The coefficient $\beta$ can be used to improve the original DDA by modifying the reduction of rockfall acceleration due to the collision:

$$[a'] = (1 - \beta)[a]$$ \hspace{1cm} (4)$$

$$[v'] = \Delta t[a'] + [v_0]$$ \hspace{1cm} (5)$$

where $[v_0]$ is the initial velocity of the block at the current calculation step; $\Delta t$ is the time interval; $[a']$ and $[v']$ are the modified acceleration and initial velocity for the next calculation step, respectively; $[a]$ is the acceleration calculated at the current step, and it can be expressed by

$$[a] = \frac{\Delta^2[D(t)]]}{\Delta t^2} = \frac{2}{(\Delta t)^2}[D] - \frac{2}{\Delta t}[v_0]$$ \hspace{1cm} (6)$$

where $[D]$ is the deformation calculated at the current step.

4 Verification of rockfall simulations

In order to verify the adequacy of the improved DDA, we conducted the simulations of rockfall at above-mentioned test site. Figure 9 shows the analytical model. In the analysis, the section between line $A$ and concrete block (big) was taken into consideration. Table 2 shows the parameters used in the analysis. The friction angle of the slope and the tree resistance coefficient were set to be zero because there was no tree at the experimental site. The collision damping coefficient was set to be one of the four values: 0.6, 0.7, 0.8 and 0.9.

Figure 10 shows the trace and the velocity of rockfall obtained. At the first cut slope, each case mainly shows sliding or rotation movement. While at the berms, collision or spring movement happens. The velocity of rockfall is suddenly damped on every berm and footline.

Figure 9 Analytical model of field experiments (the section between line $A$ and concrete block (big)).

<table>
<thead>
<tr>
<th>Stiffness of contact or constrain springs (kN/m)</th>
<th>Friction angle $\phi$ (°)</th>
<th>Shape of Rockfall and slope (m × m)</th>
<th>Collision damping coefficient $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.0 \times 10^5$</td>
<td>$2.0 \times 10^6$</td>
<td>25.9</td>
<td>0.0 $\times$ 0.5, 0.6, 0.7, 0.8, 0.9</td>
</tr>
</tbody>
</table>
Figure 11 shows the comparison of calculated and experimental results in the case of $\beta = 0.7$. The calculated results agree well with the experimental results. Furthermore, the velocity of rockfall changes continually in sliding or rotation movement, while the damping of movement changes discontinuously in collision movement. From these results, we understand that the improved DDA can describe the rockfall behavior precisely.

Table 3 shows the comparison between the calculated and the tested velocities and jumping heights of rockfall. As for the rockfall velocity, the difference between the calculated and the tested ones is within the range of $-4\%$–$7\%$ in the cases of $\beta = 0.6$, $0.7$ and $0.8$. The improved DDA simulations well reproduce the experimental results. Particularly, the case of $\beta = 0.7$ acquires the best precision. As for the jumping heights, the difference between the calculated and the tested ones is within the range of $-17\%$–$14\%$ in the cases of $\beta = 0.7$ and $0.8$.

From these results, we can find that the proposed analytical technique is validated for quantitative estimation of the velocity and jumping height of rockfall by choosing suitable values of $\beta$.

It is also known that the energy loss at the time of collision is controlled predominantly by the ground condition, or the geology of the slope, and the rockfall velocity just before collision. Therefore, the quantitative evaluation of the collision dumping coefficient that takes into account the characteristics of the slope, and the calibration of the collision dumping coefficient that considers the size of the rockfall velocity just before collision, are expected to improve the calculation precision of the method in the near future.

## 5 Conclusions

To evaluate precisely the behavior of rockfall, DDA is improved to evaluate the rockfall behaviors quantitatively. Furthermore, the validity of the improved DDA is checked by field rockfall tests. The results show that the improved DDA can evaluate the rockfall behaviors precisely.

With the improved DDA, the rockfall is simulated to introduce an independent parameter to express...
distinctly the energy losses caused by friction, collision and vegetation.

The results of field experiments show that the energy loss caused by the collision ($\beta$) is one of the most important factors. In this paper, the method for determining the collision dumping coefficient is described in detail, and its validity is confirmed by the field tests.

In addition, the experimental results indicate that the rockfall behaviors have a great unevenness. Therefore, Monte Carlo simulation technique is thought to be necessary in the future researches.

References


