Experimental and Numerical Analysis of Rock Block Stability Using a Remotely Positioned Laser Doppler Vibrometer

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Abstract: This paper examines a new method of evaluating the stability of a rock slope using a remotely positioned LDV (laser Doppler vibrometer). We conducted an experiment using physical models and performed a numerical analysis to evaluate the new method. The physical model included: (1) concrete blocks on an artificial soil slope with two block sizes and three slopes; (2) concrete blocks bonded to the concrete base with different contact area. The LDV measurements agreed with conventional seismometer measurements. The dominant frequency of the blocks varied with the stability and dominant frequency and the amplitude varied with the block size. The numerical model was used to examine a concrete block adhered to a concrete base with different contact areas. The dominant frequency of the blocks determined using the numerical model agreed with those obtained from the physical experiments. We analyzed different sized blocks to examine the scaling effects. The dominant frequency of the blocks was inversely related to the block size. These results demonstrated the effectiveness of LDV for evaluating the stability of rock slopes and cleared the block size scaling effects.

Key words: Field measurements, risks and hazards, rock failure, rock mass, stability analysis.

1. Introduction

It is necessary to evaluate the stability of rock slopes to prevent slope disasters. Measurement methods such as tonometry, electrical impedance and photographic surveys are somewhat effective. Another method evaluates the risk of rocks falling by measuring vibrations [1, 2] using highly precise seismometers installed directly in the unstable rock blocks and base. The risk associated with the rock block stability can then be determined by analyzing the vibration measurements. However, this technique has risks associated with obtaining the measurements, and is expensive. Therefore, development of the cheap, safe and quantitative evaluation technique is expected.

The influence of different rock discontinuities on the support of the rock mass as well as scaling effects of different sized rocks must be considered in some discontinuous rock masses [3]. But although the scaling effects of rock blocks are likely important when examining the stability of a rock slope, they are not considered in the techniques described above.

In addition, it was thought that the size and a state of the rock block, the hardness and the incline of the slope affected the rock block stability, but did not consider the influence of these factors in the past study almost.

For the purpose of performing stability evaluation of rock slope effectively and safely, the writers developed a rock block stability evaluation method using a remote LDV (laser Doppler vibrometer) [4-8].

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LDV is not a new technology but has been commonly used as a non-contact measurement device for vibrations, especially in laboratories [9, 10].

We carried out the model experiment that set up an unstable rock block (concrete block) on the slope, which was made to model the soil slope, to inspect whether the exact tonometry is made from remoteness. In addition, by the experiment, we examine the applicability of the remote tonometry by considering the relations of the mechanical stability of the block and the vibration properties.

Furthermore, the writers assumed unstable rock mass, carried out a model experiment and the numerical analysis that installed an unstable rock block (concrete block) on a concrete block pedestal.

By these experiments and numerical analysis, we considered the change of the block stability and the change of the vibration characteristic by the size of the block and a state, and by the incline of the slope, and examined the relations of rock block stability and the vibration characteristic. Furthermore, we examined the scaling effects of rock blocks by considering the theoretical formula of the dominant frequency and by comparing the experimental results with the numerical analysis.

2. Experiment Using a Soil Slope Model

2.1 Summary

Fig. 1 shows the laser Doppler vibrometer called “U-Doppler”, which was originally developed for non-contact measurements of vibrations for diagnosis of railway bridges [11]. One of the outstanding features of U-Doppler is applicability to outdoor environment, where there are many vibration noises shaking the sensor itself. To compensate the vibration of U-Doppler itself, another vibration sensor is installed inside it.

Fig. 2 shows a schematic diagram of our experimental model. We placed an unstable concrete block on a slope and measured the vibration of the block with a LDV. Simultaneously, we measured the block stability with an established technique using seismometers with a dominant frequency of 28 Hz installed in the block to compare the two methods. The slope was covered in river sand with particles ≤ 0.5 cm in size.

We examined various block stability parameters, including block size and state, slope hardness and incline, for a total of 26 cases using different combinations of conditions as follows:

1. Slope model—two models were used: an artificial soil slope model and flat ground;
2. Slope incline—0°, 20° and 30°;
3. Initial block position—unburied or buried, vertical or horizontal;
4. Block size—large (60 cm × 50 cm × 40 cm, about 285 kg) and small (40 cm × 30 cm × 20 cm, about 57 kg);
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(5) LDV measurement distance—18.4, 29 and 150 m;
(6) Measurement method—each set of conditions was measured six times.

Fig. 3 shows the experimental set-up. The LDV was installed 18.4-150 m from the model. The laser beam was focused on the block, while the sensor measured the reflected light. This experiment measured the horizontal vibration speed in the upper section of the block.

2.2 Results

2.2.1 Telemetry Applicability

The wave pattern of the vibration amplitude over time and its spectrum obtained from the experiments were used to compare the LDV and seismometer results (Fig. 4). In the figure, LDV corresponds to the data measured at 150 m while GP (geo-phone) corresponds to the data collected by the seismometer on the blocks. The results were obtained using a small block and model slope angle of 20°. The wave pattern record and the spectrum from both techniques showed similar patterns (Fig. 4). But, as shown in the Fig. 4b, at the point shown in the mark of the circle line, the difference in spectrum peak value is seen, the LDV was bigger than GP. It is caused by the fact that because the measurement with the seismometer used a seismometer of dominant frequency 28 Hz, the measurement sensitivity less than frequency 28 Hz become low. By these results, it was cleared that the measurements by the LDV was accurate.

2.2.2 Applicability to Evaluating Rock Block Stability

We used different experimental conditions to examine the effectiveness of the LDV for evaluating block stability by examining the dominant frequency and amplitude of each block.

Fig. 5 shows photographs of the conditions used in the experiment. We examined four cases, LD15-18. In each case, the large block, 20° incline, and an LDV distance of 18.4 m remained constant, while the block position varied. For LD15, the block was placed horizontally with the 60 cm × 40 cm side as the base; for LD16, it was placed vertically with the 50 × 40 cm side as the base, for LD17, it was placed vertically and...
buried 20 cm, and for LD18, it was placed horizontally and buried 20 cm. There were differences in stability for each block position, the horizontal blocks (LD15 and LD18) were more stable than those placed vertically (LD16 and LD17) and the buried blocks (LD17 and LD18) were more stable than the unburied blocks (LD15 and LD16).

Fig. 6 shows the results of the LDV measurements. Based on the block vibration characteristics, the dominant frequency increased and the amplitude decreased from LD16, LD17, LD15 to LD18. These results are consistent with the expected block stability. Moreover, the dominant frequency increased and amplitude decreased as block stability increased. From this, we can evaluate the block stability using the dominant frequency and amplitude of vibrations in the block.

2.2.3 Scaling Effects

We examined the differences in the vibration characteristics and stability between block sizes. Fig. 6 shows two pairs of results for LD1-16, differing only in block size. LD13 and LD14 used small blocks and LD15 and LD16 used large blocks. LD13 had a higher dominant frequency and smaller amplitude than LD16 (Fig. 7). When considered with the results in Section 2.2.2, this indicated that block stability was greater for LD13 than LD16. Differences in the length to width ratio were also considered. LD13 had a ratio of 2 (40 cm/20 cm), while LD16 has a ratio of 1.5 (60 cm/40 cm, Fig. 5). Since we assumed that the lower LD16 ratio was more stable mechanically, we also assumed that the block was not stabilized by its size, but that the scaling effects played a role in the block stability.

The dominant frequencies and amplitudes of LD14 and LD15 followed a similar trend. The scaling effects

Fig. 6 Measurement results using the LDV.

Fig. 7 Examination of the scaling effects using LDV measurements. LD13 and LD14 used small block; LD15 and LD16 used large block; LD13 and LD16 were vertical position; LD14 and LD15 were horizontal position. Common experimental conditions were slope incline: 20°; distance between LDV and model: 18.4 m.
of the block are discussed in more detail in the numerical analysis section.

3. Concrete Model Experiment

Fig. 8 shows the appearance of the concrete block models. Concrete blocks weighing 57 kg and measuring 40 cm × 30 cm × 20 cm were bonded to a horizontal L-form concrete pedestal with mortar adhesive (DK bond). We examined six cases with the blocks adhered either at the base (30 cm × 20 cm) or at the back (40 cm × 20 cm). These were adhered to the full surface, or to 1/2 or 1/4 of the surface. Three points, the block tops and bottoms and the pedestal region, were measured simultaneously using three LDVs installed 30 m from the model.

Table 1 shows the dominant frequency of the block in each case, as measured by tonometry, and compares these values with the numerical analysis results described below. The observed dominant frequency decreased with smaller adhesion areas. This suggests a correlation between the mechanical stability and vibration characteristics of the block.

4. Numerical Analysis

4.1 Numerical Analysis of the Concrete Model Experiment

To develop a block stability evaluation technique, we analyzed the results by examining the changes in vibration characteristics with mechanical stability. Using the software package Soil Plus, we performed a linear dynamic analysis of white noise input into the base of the model. Fig. 9 shows a photograph and example of an analysis model (Case 6Q), the vibration output in the analysis is indicated with an arrow. Fig. 10 shows the results of a one-block vibration analysis. The analysis results are summarized in Table 1.

As shown in Fig. 10 and Table 1, the dominant frequency decreased with the adhesion area (Cases 6, 6H, 6Q; Cases 3, 3H, 3Q). This tendency is consistent with the positive correlation between the block mechanical stability and adhesion area.

4.2 Destruction Case

According to the experiment results and the analysis results for the concrete model, it was estimated that the elastic coefficient of the DK bond which we used for the adhesion of the block this time was at the same level or a higher as concrete. And it was cleared that the bond strength was too strong to let the block destabilize at the adhesion area of the experiment shown in Fig. 8.

Therefore, about Case-6Q thought to be the instability extremely, we gradually deleted the adhesion side with a concrete drill and performed tonometry while reducing the adhesion area. After deleting the adhesion width from 7.5 cm to 3 cm by the experiment sequentially, and being going to delete it in 3 cm or less more, the adhesion side destroyed. It was with 45 Hz (Fig. 10) when we found dominant frequency in the case of 3 cm by numerical analysis, and it was cleared that the dominant frequency was a

Fig. 8  Concrete model.
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Table 1  Comparison of the dominant frequency obtained in the model experiment and the numerical analysis.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model experiment (Hz)</th>
<th>Numerical analysis (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 3</td>
<td>-</td>
<td>252</td>
</tr>
<tr>
<td>Case 3H</td>
<td>400</td>
<td>230</td>
</tr>
<tr>
<td>Case 3Q</td>
<td>200</td>
<td>147</td>
</tr>
<tr>
<td>Case 6</td>
<td>455</td>
<td>310</td>
</tr>
<tr>
<td>Case 6H</td>
<td>275</td>
<td>210</td>
</tr>
<tr>
<td>Case 6Q</td>
<td>107</td>
<td>111</td>
</tr>
</tbody>
</table>

Fig. 9  Photograph and model of Case 6Q.

Fig. 10  Example of the block vibration analysis.

- Red line: Upper part; Green line: Lower part
near value to the observation level (51 Hz) [5].

4.3 Scaling Effects

To examine the scaling effects, we conducted a numerical analysis using models five and ten times larger than the destruction case (Fig. 11). The results of the analysis showed that the dominant block frequency was inversely related to the block size.

Fig. 12 shows the analysis model and the results for five times model. As shown in Fig. 12a, the adhesion width was 15 cm, five times larger than the destruction case. And the dominant frequency of the block was 9 Hz, which was about 1/5 times of the destruction case.

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**Fig. 11** Analysis model and the analysis results for the destruction case.

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**Fig. 12** Analysis model and the analysis results for five times model.
5. Consideration by Theoretical Formula

We examined the relationships between the dominant frequency obtained from the numerical analysis and the dimensions of the block by using the theoretical formula of the dominant frequency. We assumed that the analysis model bent the vibration mode of the beam, and that the dominant frequency \( f \) of the block could be expressed as:

\[
f = \frac{1}{2\pi} \left( \frac{EI_0}{\rho A} \right)^{1/2} \left( \frac{\pi^2}{l^2} \right)^2
\]  

(1)

where, \( \rho \) = adhesive material density, \( E \) = adhesive material elastic coefficient, \( A \) = adhesion area, \( I_0 \) = second section moment of the adhesive, and \( l \) = adhesive thickness. When the length is expressed as \( L \), the relationships of \( I_0, A, \) and \( l \) with \( L \) is as follows:

\[
I_0 \propto L^4
\]

\[
A \propto L^2
\]

\[
l \propto L
\]

(2)

The relationship of \( f \) with \( L \) is given by:

\[
f \propto L^{-4}
\]

(3)

Therefore, there was a relationship between the dominant frequency and the dimensions of the block.

6. Conclusions

The experiment using physical model (1) concrete blocks on an artificial slope and model (2) concrete blocks bonded to the concrete pedestal, and the numerical analysis for model (2) were performed. In the experiment and the analysis, the dominant frequency and amplitude of the block was examined.

By the experiment using physical model (1), the dominant frequency and the amplitude by LDV was agreed with conventional seismometer, inspected that the LDV can make accurate block vibration measurements, and that the dominant frequency and amplitude of vibrations in a block are related to the block stability. Furthermore, we founded that the dominant frequency and amplitude of the blocks varied with the stability, and the dominant frequency and the amplitude varied with the block size and the block state. The dominant frequency increased and amplitude decreased as block stability increased. From these results, it was cleared that we can evaluate the block stability using the dominant frequency and amplitude of vibrations in the block.

By the experiment using physical model (2), it was cleared that the observed dominant frequency decreased with smaller adhesion areas. This suggests a correlation between the mechanical stability and vibration characteristics of the block.

By the numerical analysis for model (2), the tendency and the value of the dominant frequency obtained by the analysis was agreed with the experiment results. Furthermore, the results of the analysis showed that the dominant frequency of the block was inversely related to the block size. This matched with the examined results using the theoretical formula.

These results demonstrated the effectiveness of LDV for evaluating the stability of rock slopes and cleared the block size scaling effects.

References


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