Study on evaluating rock block stability by 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 laser Doppler vibrometer (LDV). An experiment program was conducted by using physical models and a numerical analysis was performed to evaluate the new method. 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. These results demonstrated the effectiveness of LDV for evaluating the stability of rock slopes.

Keywords: Model 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 seismmometers 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.

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 order to evaluate the stability of rock slopes, Ma et al. [4-7] developed a rock block stability evaluation method using a remote laser Doppler vibrometer (LDV). In this study, an experiment program was conducted by using physical models and a numerical analysis was performed to evaluate the effectiveness of the new method. Furthermore, the scaling effects of rock blocks was examined by using a similar method and by performing a numerical experiment.

2. EXPERIMENT USING A SOIL SLOPE MODEL

2.1 Summary

Figure 1 shows a schematic diagram of the experimental model. An unstable concrete block was placed on a slope and measured the vibration of the block with a LDV. Simultaneously, the block stability was measured with an established technique using seismmometers installed in the block to compare the two methods. The slope was covered in river sand with particles ≤ 0.5 cm in size.

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

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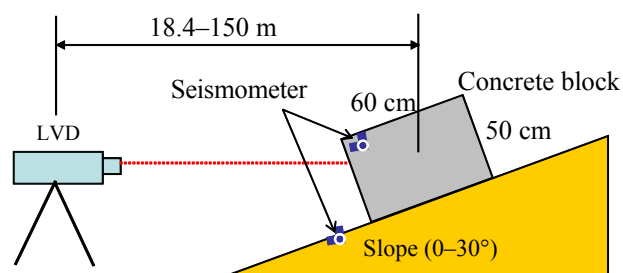- Measurement method – each set of conditions was measured six times.

Figure 1. Schematic view of the experimental model

Figure 2 shows the experimental set-up. The laser Doppler (LD) of 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.
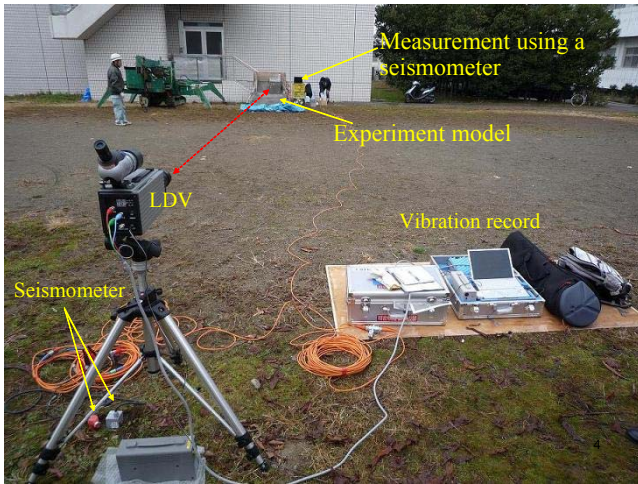
Figure 2. Placement of the apparatus

2.2   Telemetry applicability

The wave pattern of the vibration amplitude over time and its spectrum obtained from the experiments were used to compare the LD and seismometer results (Figure 3). In the Figure, LD corresponds to the data measured at 150 m while GP 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 (Figure 3), indicating that the remote measurements made using the LD were accurate.
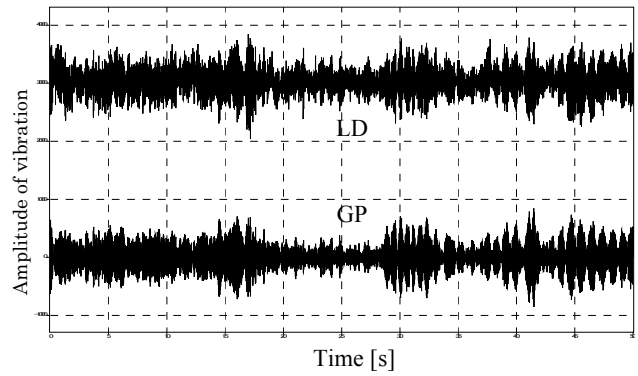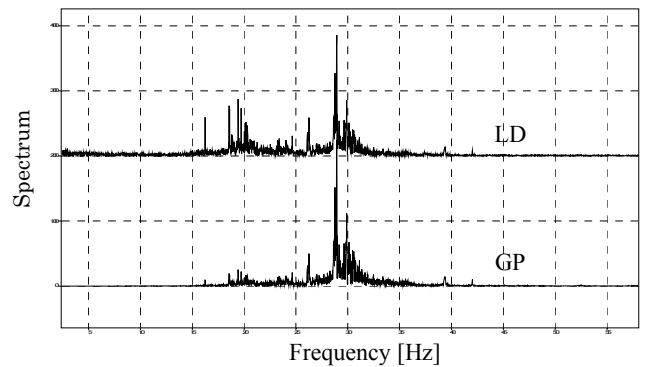
2.3   Applicability to evaluating rock block stability

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

Figure 4 shows the conditions used in the experiment. Four cases were examined, LD15–18. In each case, the large block, 20° incline, and an LD distance of 18.4 m remained constant, while the block position varied. For LD15, the block was placed horizontally with the 60×40-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).

Figure 5 shows the results of the LDV measurements under these conditions. 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.

(a) Vibration amplitude over time

(b) Spectrum obtained from the experiment
Figure 3. Comparison of the LD and seismometer results
LD: Measurements using the LDV installed 150 m from the model. GP: Measurements using the seismometer installed in the block at a dominant frequency of 28 Hz.
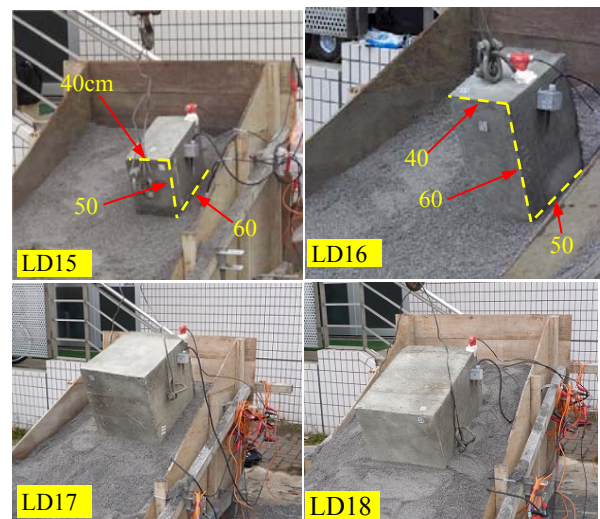

Figure 4. Photographs of the experimental conditions
LD15, horizontal position; LD16, vertical position;
LD17, vertical position and buried 20 cm;
LD18, horizontal position and buried 20 cm.

2.4 Scaling effects

The differences in the vibration characteristics and stability between block sizes were examined. Figure 6 shows two pairs of results for LD13–16, differing only in block size. LD13 and LD14 used small blocks and LD15 and LD16 used large blocks.
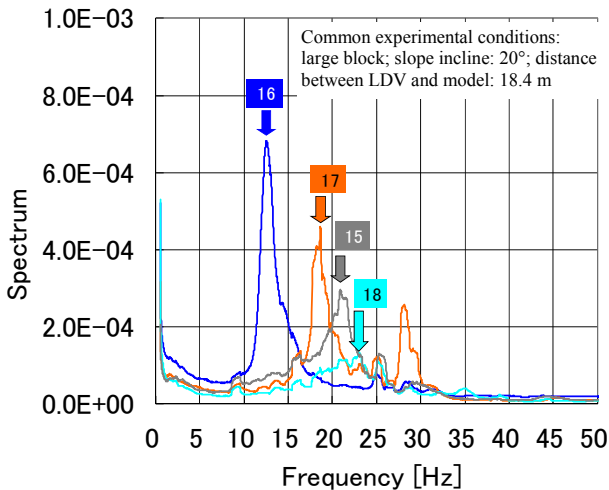
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Figure 5. Measurement results using LDV

LD13 had a higher dominant frequency and smaller amplitude than LD16 (Figure 6). 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 (60cm/40 cm; Figure 4). 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.

A similar trend was showed in the dominant frequencies and amplitudes of LD14 and LD15. The scaling effects of the block are discussed in more detail in the numerical analysis section.
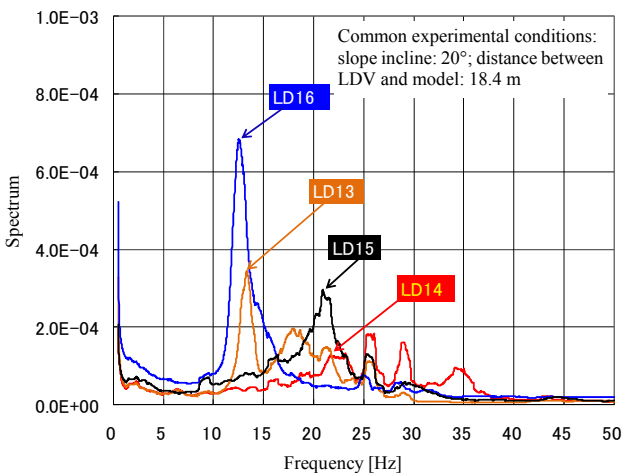

Figure 6. Examination of the scaling effects using LDV measurements
LD13 and LD14, small block; LD15 and LD16, large block; LD13 and LD16, vertical position; LD14 and LD15, horizontal position

3 CONCRETE MODEL EXPERIMENT

Figure 7 shows the appearance of the concrete block models. Concrete blocks weighing 57 kg and measuring 40×30×20 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 (30×20 cm) or at the back (40×20 cm). These were adhered to the full surface, or to ½ or ¼ 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.
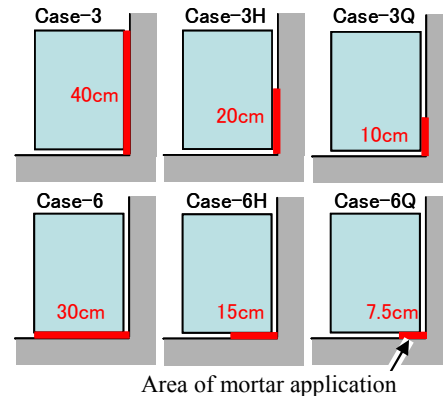

Area of mortar application

Figure 7. Concrete model

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 SoilPlus, we performed a linear dynamic analysis of white noise input into the base of the model.

Figure 8 shows a photograph and example of an analysis model (Case 6Q); the vibration output in the analysis is indicated with an arrow.

Figure 9 shows the results of a one-block vibration analysis. The analysis results are summarized in Table 1. In addition, we used physical properties that was similar to adhesion materials DK bond with concrete, Young's modulus $2.2E+7kN/m^2$, Poisson ratio 0.2, density $21kN/m^3$ for analysis to show in Figure 9.

As shown in Figure 9 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 Numerical analysis just before the destruction

According to the comparison between model laboratory finding and numerical analysis results, it was estimated that the Young's modulus of the DK bond used for the adhesion in this times was same or higher level as concrete. So it was understood that the bond strength was too strong to let the block destabilize at the adhesion area of this experiment. Therefore , about Case-6Q thought to be the reasonable instability, we gradually deleted the adhesion side with a concrete drill and performed tonometry while reducing an adhesion area. The adhesion width was deleted with 6cm, 5cm, 3cm from 7.5cm by the experiment sequentially, and when delete it in under 3cm, the adhesion side destroyed. The dominant frequency was 45Hz (Figure 10) in case of 3cm by numerical analysis, it was near to observation value 51Hz.

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

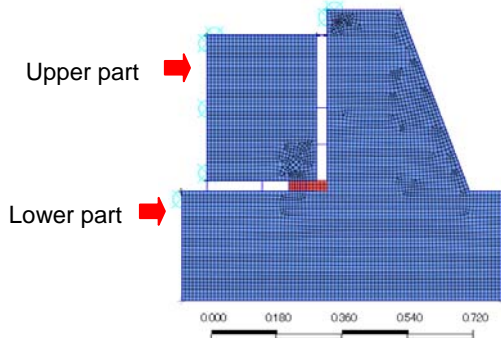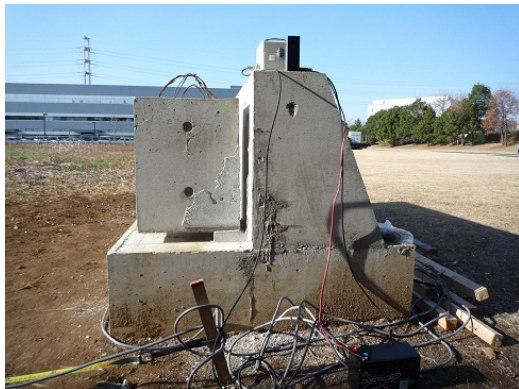| Model	Model experiment [Hz]	Numerical analysis [Hz]
Case 3	-	252
Case 3H	400	230
Case 3Q	200	147
Case 6	455	310
Case 6H	275	210
Case 6Q	107	111

Figure 8. Photograph and analysis model of Case 6Q

4.3 Scaling effects

To examine the scaling effects, a numerical analysis was conducted using models five and ten times larger than the experimental model (The case of just before destruction, refer to Figure 10).

Figure 11 shows the analysis result of vibration in the case of five times model. The dominant frequency provided in

the five times model becomes smaller than the 1 time model (45Hz) at approximately 9.0Hz. Similarly , the analysis of the 10 times model got dominant frequency approximately 4.2Hz. From the analysis results of 1 time, 5 times and 10 times model, it can be surmised that the dominant frequency of the block was inversely related to the block size (Refer to Figure 12).
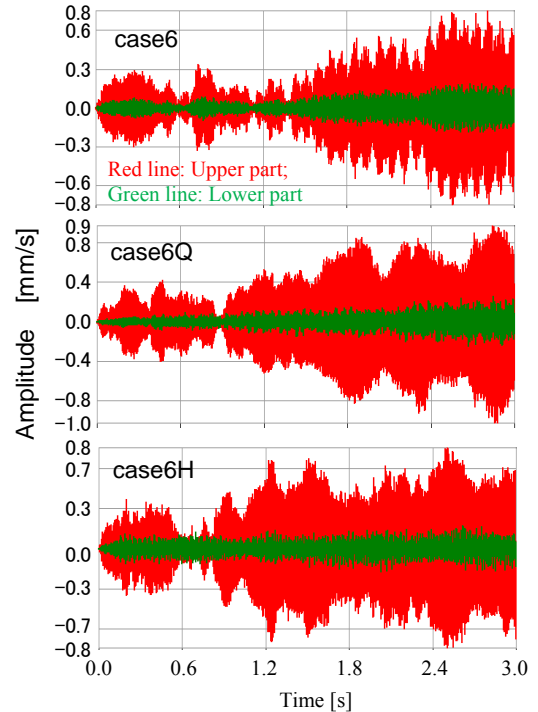
(a) Vibration history
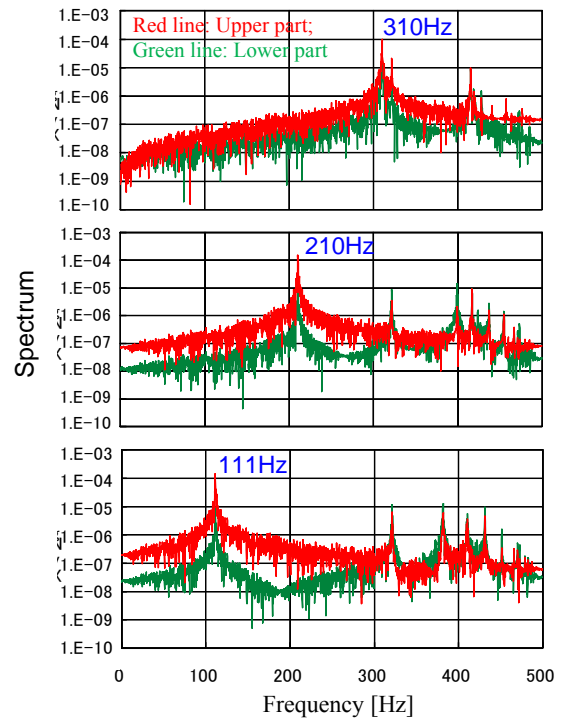
(b) Velocity spectrum of the vibration

Figure 9. Example of the block vibration analysis
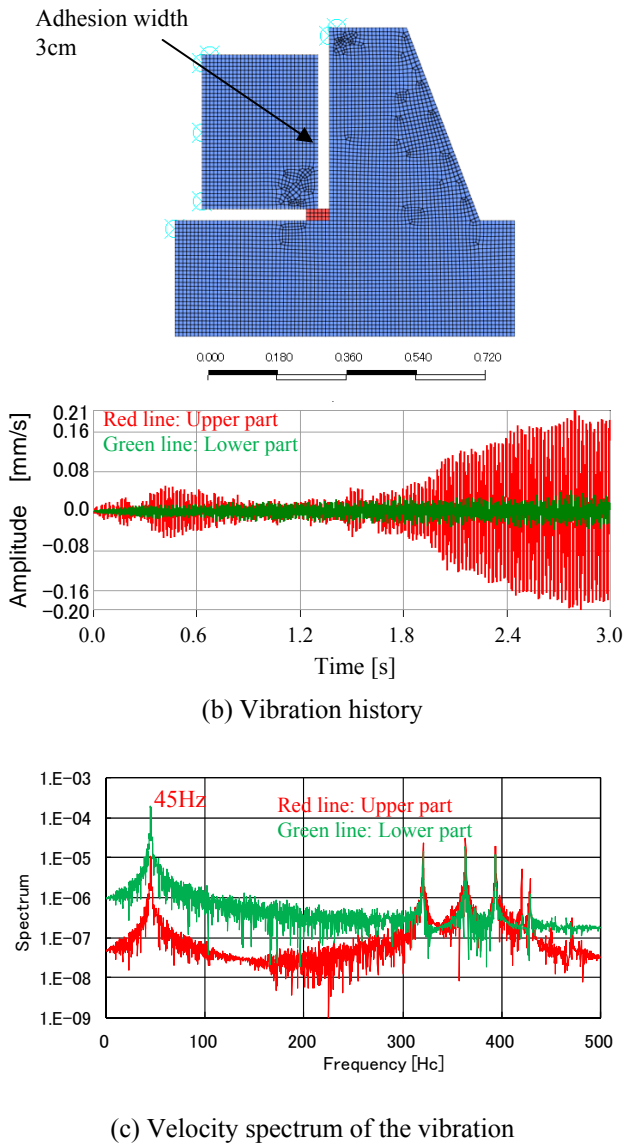Upper part and Lower part: Refer to Figure 8

Adhesion width
3cm

(b) Vibration history

(c) Velocity spectrum of the vibration

Figure 10 Analysis result of vibration in the case of 3cm

4.4 Examination of scaling effects by similarity

The relationship between the dominant frequency obtained from the numerical analysis and the dimensions of the block by using the similarity of the dominant frequency was examined. It was assumed that the analysis model was bent vibration mode of a beam, and that the dominant frequency f of the block could be expressed as:

$$f = \frac{1}{2\pi} \times \left(\frac{EI_0}{\rho A} \right)^{1/2} \times \left(\frac{\pi}{l} \right)^2 \qquad (1)$$

where ρ = 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 are as follows:

$$I_0 \propto L^4$$
$$A \propto L^2 \qquad (2)$$
$$l \propto L$$

The relationship of f with L is given by:

$$f \propto L^{-1} \qquad (3)$$

Therefore, the relationship between the dominant

frequency and the dimensions of the block provided by numerical analysis matches the similarity of dominant frequency.

Adhesion width
15cm

(a) Analysis model

(b) Vibration history
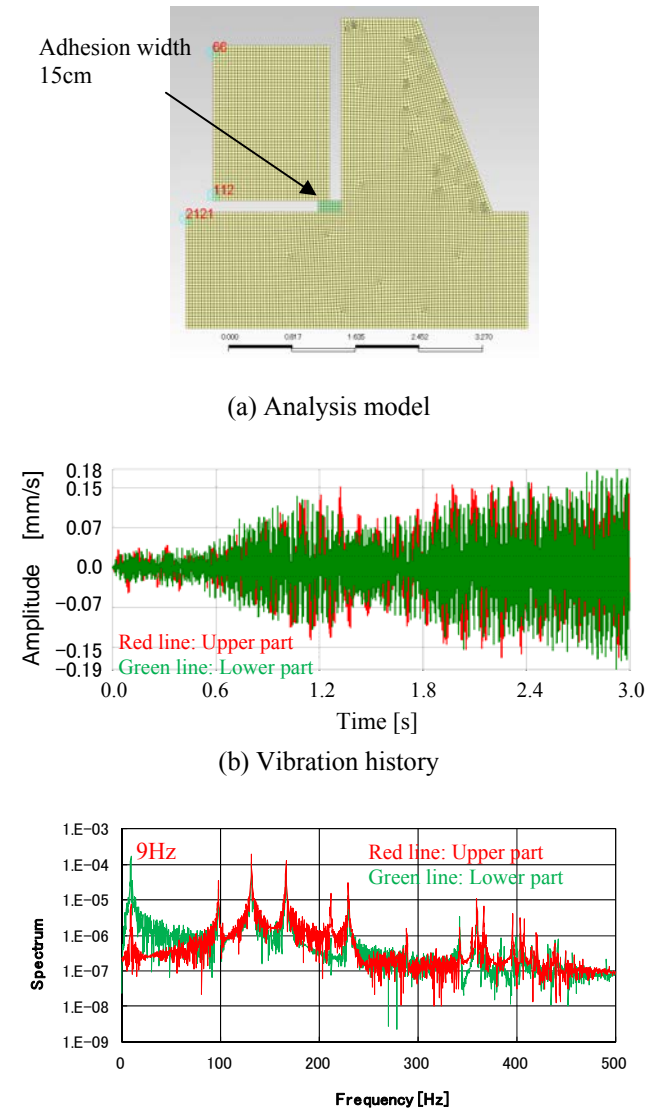

(c) Velocity spectrum of the vibration

Figure 11 Analysis result of vibration in the case of five times model
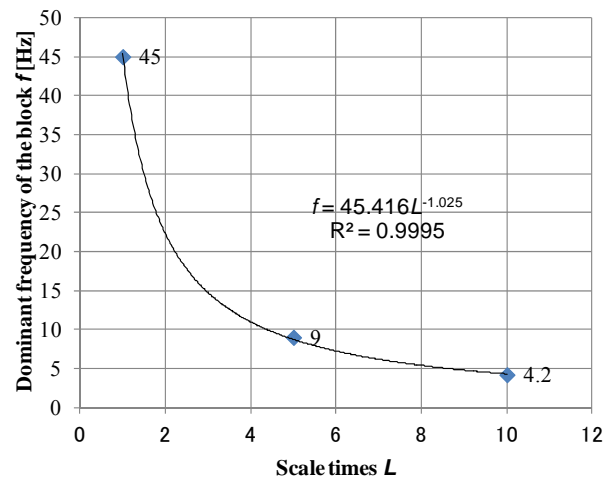

Figure 12 Relations with dominant frequency and the dimensions of the block

5 CONCLUSIONS

The model experiment of the soil slope model and the concrete model were carried out by the remote tonometry. In addition, the numerical analysis of the concrete model experiment was carried out to examine the change of vibration properties by the stability change of the block, and examine the scale effect of the block.

The experiment results of soil slope model determined that 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, from the experiment results of soil slope model and the numerical analysis of the concrete model, we found that the dominant frequency of vibrations in the block was inversely proportional to the size of the block. And the relationship between the dominant frequency and the dimensions of the block provided by numerical analysis matches the similarity of dominant frequency.

By model experiment of the concrete model, the dominant frequency decreased with the adhesion area. The tendency of dominant frequency is consistent with the positive correlation between the block mechanical stability and adhesion area. And the numerical analysis reappeared the tendency. These results showed the validity of the model experiment and the numerical analysis.

6 ACKNOWLEDGMENT

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