Fundamental Study on the Remote Vibration Measuring System for Evaluating Rock Slope Stability

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SUMMARY:
The authors have been studying on the evaluation method of rock slope stability by applying a non-contact vibration measuring system termed as "U-Doppler" that has been developed by implementing various improvements to the Laser Doppler Velocimeter (LDV) for use in the field. The purpose of the study is to develop the evaluation system and method for rock slope stability by measuring vibration of rocks. First, the 3D remote vibration measurement system for rock slope was developed. Next, as the remote control system to form the reflective targets on a distant rock slope, the RC helicopter was developed that mounted the reflective paint spray device. Lastly, based on the results of the model experiments by using concrete blocks bonded to the concrete base with different adhesion condition, a new method of rock stability evaluation was proposed.

Keywords: rock slope stability, remote measurement, LDV, predominant frequency, safety factor

1. INTRODUCTION

In Japan, the railway network has extended to the mountainous area, and the rock fall measures are very important. Figure 1 shows the examples of the large-scale rock fall due to earthquake, and Figure 2 shows the examples of derailment damage by falling rock by other causes. The early detection method of an unstable rock block is indispensable to prevent the railway damage by a falling rock. Many conventional stability evaluation methods are based on techniques and know-how of specialist of geology and civil engineering. However, it is difficult to identify unstable rocks accurately only by the visual inspection because of the existence of invisible cracks behind the rock blocks.

Recently, some techniques for rock slope evaluation by means of vibration measurements have been developed (Ogata, et al. 2003, Fujisawa et al. 2007). Those techniques apply the vibration characteristics of rock block such as predominant frequency and accumulated amplitude as a risk assessment index of rock block falling; however, involve the dangerous measurement works on a steep rock slope.

The authors have been studying on the evaluation method of rock slope stability by applying a non-contact vibration measuring system termed as "U-Doppler" that has been developed by implementing various improvements to the Laser Doppler Velocimeter (LDV) for use in the field (Uehan, 2008). Adoption of a long-distance remote measurement method enables to improve the efficiency and safety of the measurement works, since it is unnecessary to install sensors and cables at locations high above rock slopes and remove them later.

The purpose of the study is to develop the evaluation system and method for rock slope stability by measuring vibration of rocks. First, the 3D remote vibration measurement system for rock slope was developed (Uehan et al. 2010). Next, as the remote control system to form the reflective targets on a distant rock slope, the RC helicopter was developed that mounted the reflective paint spray device. Lastly, based on the results of the model experiments by using concrete blocks bonded to the concrete base with different adhesion condition (Murata, et al. 2011), a new method of rock stability evaluation was proposed.

Figure 1. Examples of the large-scale rock fall due to earthquake

Figure 2. Examples of derailment damage by falling rock

2. DEVELOPMENT OF REMOTE MEASUREMENT SYSTEM FOR ROCK SLOPE

2.1. Outline of the "U-Doppler"

The author developed the U-Doppler (Figure 3, Table 1), a long-distance non-contact vibration measuring system for the diagnosis of railway structures that offers enhanced safety and efficiency by implementing various improvements to the LDV for use in the field (Uehan, 2008). The U-Doppler sensor is placed on a tripod near the structure to be measured and the laser is irradiated to the structure. The vibration (velocity) of the structure can be measured using this approach in the same way as when a sensor is fitted to the structure.

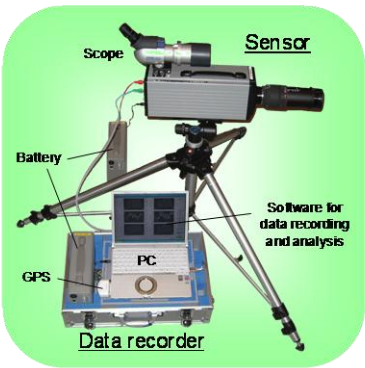

Figure 3. U-Doppler

Table 1. Specifications of Sensor Unit

Dimensions and weight	113(W)×141(H)×351(D) mm, 5.5 kg
Power supply	Battery (operation time: 8 hours) or AC adapter
Laser protection class	Eye-safe class II visible He-Ne gas laser
Velocity range	0.2 μm/s to 100 mm/s
Frequency range	DC to 600 Hz
Working distance	1.0 to 100 m (surface dependent)

The main technical feature of the U-Doppler is the compensation function using the built-in sensor. Because the LDV is a device that detects the relative velocity between the LDV itself and the object being measured, accuracy decreases when it is used to measure structural vibrations outdoors, as a result of the vibration of the LDV itself caused by various ground vibrations and/or the wind. In addition to the LDV optical sensor, the sensor unit of the U-Doppler incorporates a contact vibrometer with the same sensitivity and phase properties as the optical sensor. The influence of U-Doppler sensor vibration is removed by using the time-history data recorded by the installed vibrometer.

It is possible to measure vibrations of a variety of magnitudes from several dozen meters away, from relatively large vibrations of structures from a passing train to microtremors.

2.2. Applicability to measurement of rock slope vibration

First, the site measurement of the rock block vibration was executed, and the applicability of the U-Doppler was investigated. Figure 4 shows the measurement situations. The U-Doppler sensor was installed on the roadside under the rock slope, and the microtoremor of the extremely unstable lock block was measured.

The distance between the sensor and the rock was 200m, and the angle of elevation was 35.3 degrees. At this stage, the reflecting prism was used as a reflection target for the remote measurement, and the seismograph installed on the rock block (Figure 5) measured the microtremor simultaneously.

Figure 6 shows the measured waveforms (time series of velocity), and Figure 7 shows those Fourier spectra. From these results, we confirmed that the U-Doppler was applicable to rock slope vibration measurement when the reflectivity of the rock surface could be improved.

Figure 4. Situation of rock block measurement

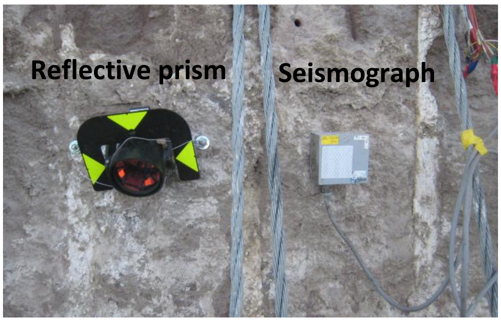

Figure 5. Reflective prism and seismograph

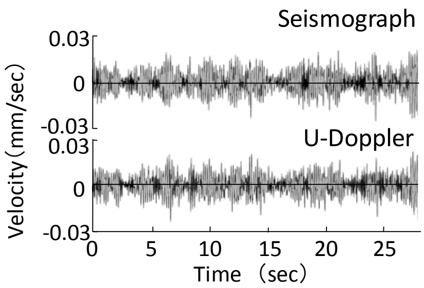

Figure 6. Waveform of measured microtremor

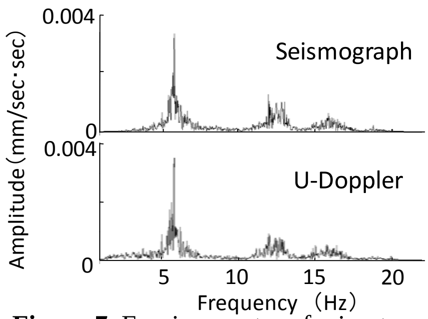

Figure 7. Fourier spectra of microtremor

2.3. Development of remote vibration measurement system for rock slope

The dominant direction of a rock block vibration is related to the state of the backside crack of the rock block. By the conventional technique, the rock block vibration is measured with the three-component seismograph, and the vibration locus is used as one of the stability criterions. On the other hand, the U-Doppler is a one component vibrometer for the direction of laser irradiation.

Then, we developed the 3D remote vibration measurement system as shown in Figure 8. This system can control three sets of U-Doppler by wireless LAN communication, and can carry out synchronous measurement. The measurement is executed from three different directions as shown in Figure 9.

Three-dimensional velocity of the rock block is estimated by expression (1).

$$\begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} = \begin{bmatrix} \cos\theta_{x1} & \cos\theta_{y1} & \cos\theta_{z1} \\ \cos\theta_{x2} & \cos\theta_{y2} & \cos\theta_{z2} \\ \cos\theta_{x3} & \cos\theta_{y3} & \cos\theta_{z3} \end{bmatrix}^{-1} \begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix} \tag{1}$$

Here, v_i is a velocity measured by the U-Doppler$_i$. θ_{xi}, θ_{yi}, and θ_{zi} are the angles between the laser irradiated by U-Doppler$_i$ and the rectangular coordinate axes X, Y, and Z, respectively. v_x, v_y, and v_z are the 3D velocity of the rock block in the rectangular coordinate system. The dominant direction of rock block vibration can be estimated by the principal component analysis on the time series of 3D velocity data. The stability assessment indices, such as predominant frequency, can be estimated for the principal component.

Figure 8. 3D remote vibration measurement system

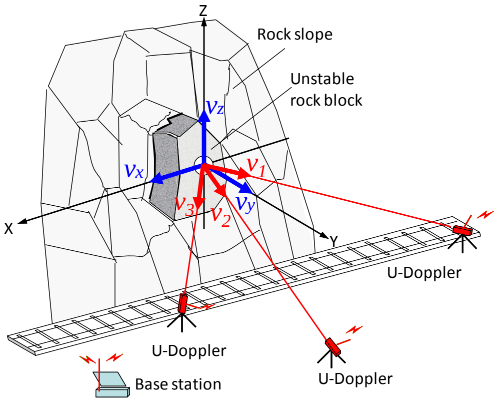

Figure 9. 3D remote measurement of rock slope

2.4. Laboratory experiment of remote 3D vibration measurement

To verify 3D vibration measurement performance of the system, the laboratory experiment was executed. The measuring object was the small rock installed on the 3D shaking table as shown in Figure 10. The rock was excited in the E-W (frequency: 4.0Hz, amplitude: 10mm), N-S (frequency: 2.0Hz, amplitude: 10mm), and U-D (frequency: 2.0Hz, amplitude: 15mm) directions. Three sensors were installed as shown in Figure 11, and the sampling frequency was 200Hz.

Figure 12 shows the 3D displacement of the rock calculated from the measured velocity data. The Lissajous figures show that the amplitude and the frequency of the rock were detected accurately by the measuring system.

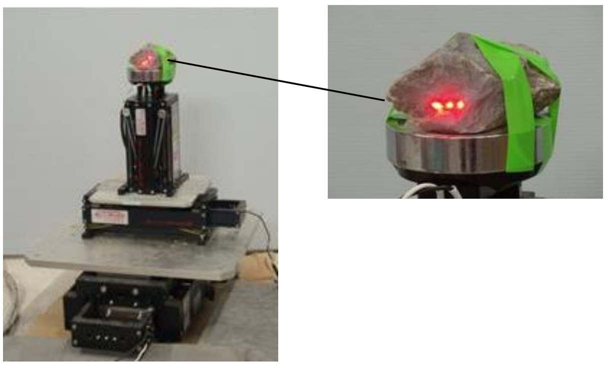

Figure 10. 3D shaking table and measuring object

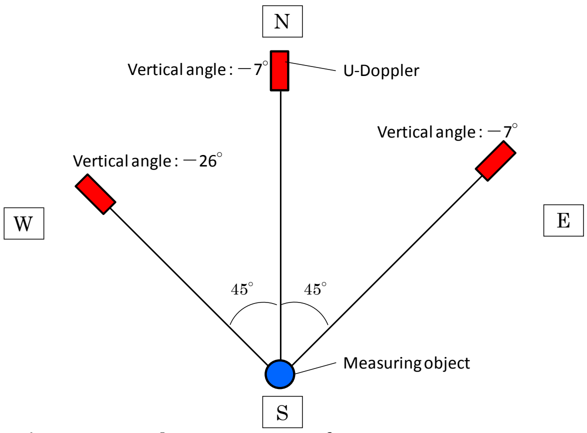

Figure 11. Schematic view of sensor arrangement

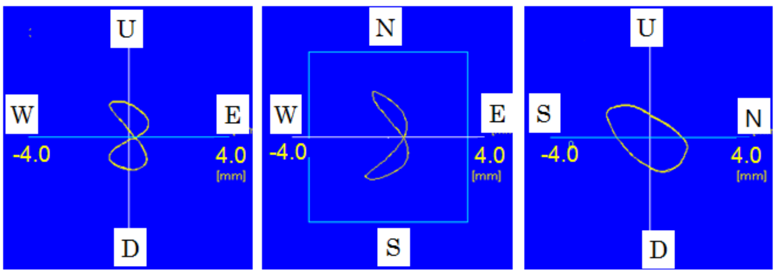

Figure 12. 3D displacement of the rock calculated from the measured velocity data

2.5. Field experiment of vibration measurement of unstable rock block

The remote measurement was executed of three rock block in the rock slope as shown in Figure 13. Rock block 1(Figure 14) was the most unstable because there were the severe cracks in the back. The remote sensors are set on the ground at the distance of 10 to 20m from the rock slope, and the reflective paint was applied to the rock surface. For the comparison, the seismograph was installed on the rock block 1 and the vibration was measured simultaneously. The sampling frequency was 200Hz.

Figure 15 is an example of the simultaneous measurement result of the three rock blocks. In this case, the vibrations generated by jumping on the rock slope were measured from the orthogonal direction to the slope. From the figure, we can clearly see the differences of vibration between unstable rock block 1 and stable rock blocks.

Figure 16 shows the Fourier spectra of the vibration of rock block 1. In this case, the vibration of predominant direction was estimated by the 3D remote measurement. The result of the remote measurement system was corresponding to the result of seismograph. The predominant frequency of the rock block 1 was approx 30Hz, and it means that the rock block 1 might be unstable (Ogata, et. al. 2003).

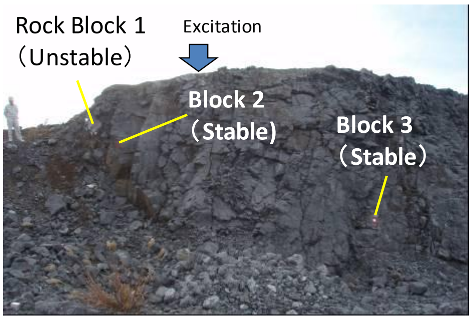

Figure 13. Rock slope and measured rock blocks

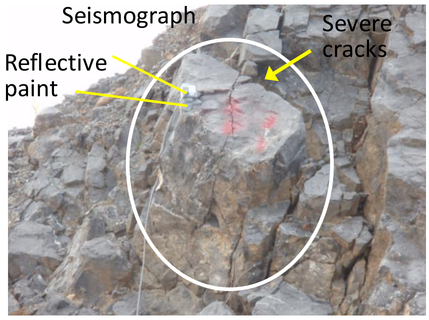

Figure 14. Rock block 1 (Unstable)

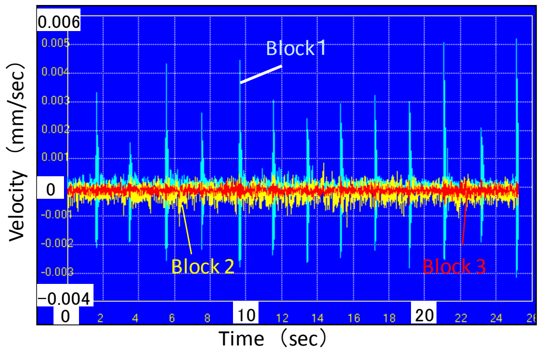

Figure 15. Simultaneous measurement results of three rocks

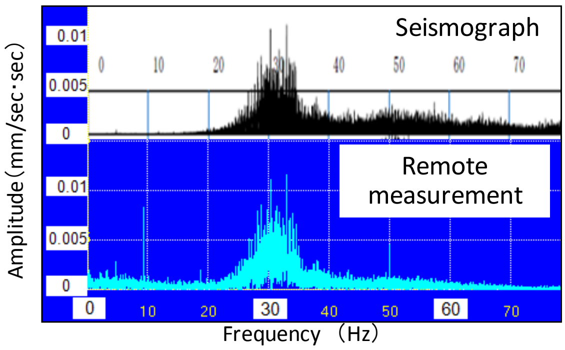

Figure 16. Fourier spectra of the rock block 1

3. REMOTE CONTROL SYSTEM TO FORM REFLECTIVE TARGETS

3.1. Improvement of laser reflectivity of rock surface

In many occasions, it is inevitable to improve the reflectivity of measured points where the vibration measured with the LDV. However, the installation of the reflective target decreases the safety and efficiency of remote measurement work on a steep rock slope. So, we developed the remote reflective target marking system.

The high performance reflective paint was developed that can improve the laser retro-reflectivity of rock surface. The reflective paint contains a number of minute glass beads with which the hemisphere part is covered with aluminium reflective layer. We confirmed that the reflective paint had high applicability to the rock surface, and developed new reflective paint that had approx 1.5 times reflectivity of a conventional paint. The reflective paint enables the remote measurement at least 100m away.

As shown in Figure 17, the reflective paint can be painted on the nearby rock with the stretchable pole device that installs the reflective paint spray. Moreover, we can use the device shown in Figure 18. The paint ball is shot from the launcher to the measurement point. As the paint ball hit the rock, its frangible shell breaks on impact and the reflective paint adhere to the rock surface. The launcher's shooting range is approximately 30m.

Figure 17. Stretchable pole device and formed target

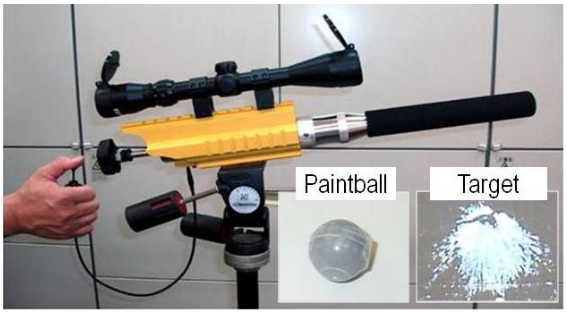

Figure 18. Paint ball launcher and formed target

3.2. Development of remote control system to form reflective target on a distant rock slope

As the remote control system to form the reflective targets on a distant rock slope, we developed the RC helicopter that mounted the reflective paint spray device and the attitude control system. Figure 19 shows the developed system. The video camera and the range finder are installed in this system. By using transmission information from them, we can form the reflective target to the rock in 100m distance. The attitude control by GPS (Global Positioning System) and IMU (inertial measurement unit) is applied to this system, and even non-expert can control the RC helicopter.

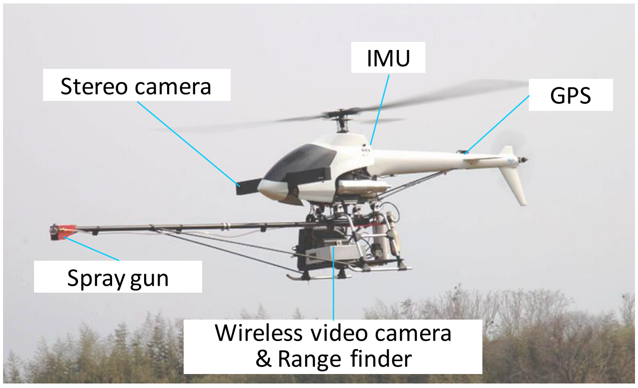

Figure 19. Remote control system to form reflective target on a distant rock slope

3.3. Field experiment of remote target marking system

The field experiment was executed by using the remote target marking system. The height of the subject rock slope was 25 m. Figure 20 shows the experimental condition and the reflective targets formed by the system. By using the developed system, we could form a reflective target in any position. Furthermore, we confirmed that the formed targets were utilizable for the microtremor measurement of rock slope.

The remote target marking system is utilizable also for collection of visual information. Figure 21 shows the subject rock slope 50 m in height and the photograph of the unstable rock lump located in the middle of the slope. The obtained image can be used also for the visual inspection.

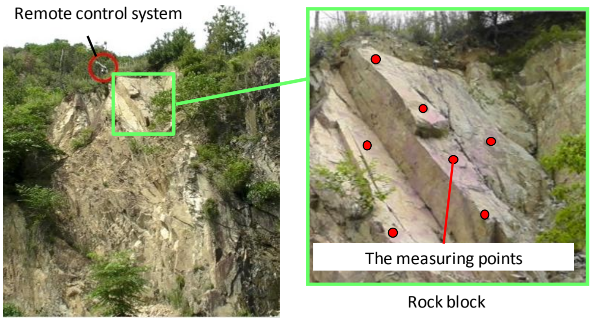

Figure 20. Experimental condition and formed targets

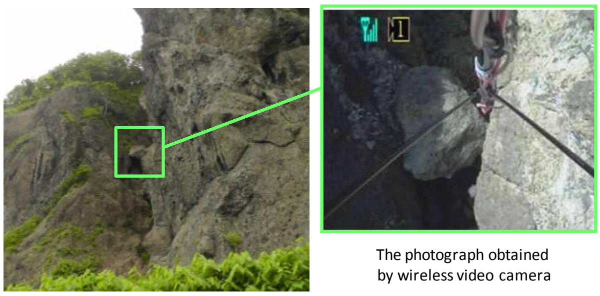

Figure 21. Rock slope and the photograph of rock lump

4. RELATION BETWEEN MECHANICL STABILITY AND PREDOMINANT FREQUENCY

4.1. Physical model experiment

In order to establish a quantitative evaluation method for rock block stability, it is required to find a relationship between the mechanical stability and the vibration characteristics. Therefore, we executed the physical model experiments. What we would like to simulate by physical modeling is a rock block just detaching from the rock mass. In general, a rock block is getting unstable due to crack extension between block and rock mass. In other words, the connecting area between them is getting smaller. We decided to use concrete block bonding on a concrete base so that we can easily change the block stability by changing the bonding area between the block and base.

Figure 22 shows the physical model and measuring system. We used two kinds of plasters as shown in Table 2 to bond concrete blocks on the concrete base, and three kinds of concrete blocks with different sizes as shown in Figure 23 to examine the effect of size on the vibration characteristics. The bonding plaster is sawn to reduce the bonding length. The vibration of the block generated by hitting the concrete base with a wooden hammer is observed by U-Doppler at some bonding lengths.

Figure 24 shows the experiment results for 6 cases, in which differences of block sizes are distinguished by the kind of symbols (square, triangle, or circle), and differences of the kind of plasters are distinguished by open or solid symbols. As the results, we found that the relationship between bonding length and dominant frequency is almost linear, and the relation was affected by the block size and the physical properties of adhesive.

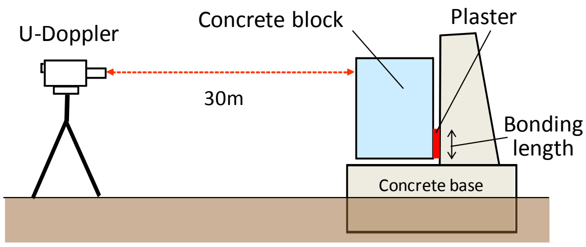

Figure 22. Schematic view of experiments

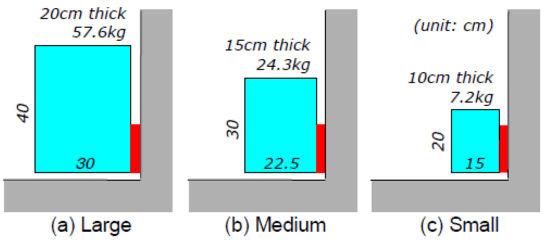

Figure 23. Concrete brocks having similarity shape

Table 2. Mechanical properties of two kinds of plasters

plaster type	gypsum: water ratio	uniaxial compressive strength	Young's modulus	splitting tensile strength
		(MN/m²)		
Grade A*	1:0.8	3.51	2,290	0.848
Hi-stone HLP*	1:0.4	17.3	7,870	2.91

* These are the product names of Yoshino Gypsum Co., Ltd.

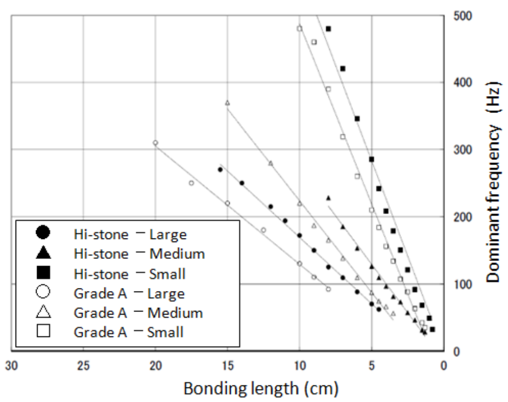

Figure 24. Relationship between bonding length and dominant frequency

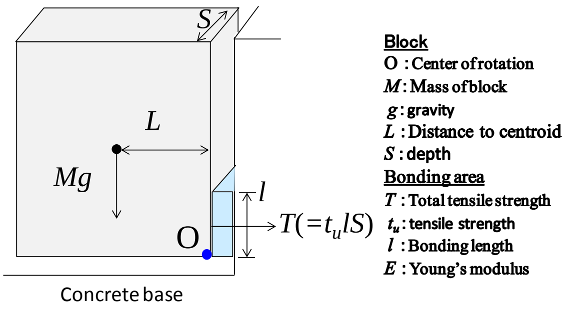

Figure 25. The model of the concrete block

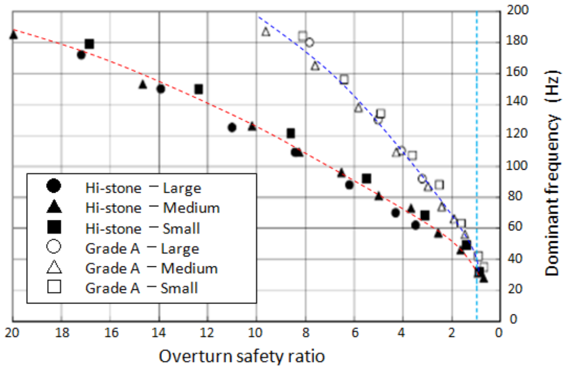

Figure 26. Relationship between overturn safety ratio and dominant frequency

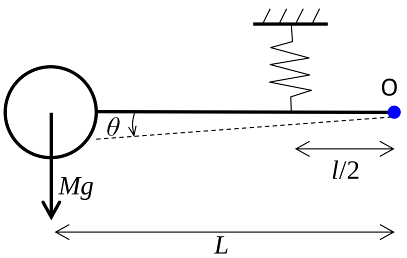

Figure 27. Simplified Experimental model

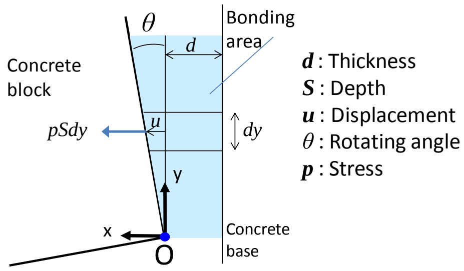

Figure 28. The bonded part model of block and base

4.2. Relationship between dominant frequency and safety ratio

In order to clarify the relation between mechanical stability and vibration characteristics, we investigated the relation between the overturn safety ratio and dominant frequency of the blocks. The overturn safety ratio was defined as the ratio of overturning moment and the maximum resistance moment of the block. The overturn safety ratio F_S of the block shown in Figure 25 is given by Expression (2).

$$F_S = \frac{(T \cdot l/2)}{Mg \cdot L} = \frac{t_u \cdot l^2 S}{2MgL} \tag{2}$$

Figure 26 shows the relation between overturn safety ratio and dominant frequency of the physical model experiments. As the results, we found that the block size hardly influenced the safety ratio-dominant frequency curves, and the frequency when the safety ratio becomes one is approximately 30Hz.

4.3. Confirmation by theoretical analysis

Figure 27 shows the simplified experiment model. The motion equation is shown in expression (3) and the natural frequency is shown in expression (4).

$$ML^2\ddot{\theta} + \frac{ESl^3}{3d}\theta = 0 \tag{3}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{ESl^3}{3dML^2}} \tag{4}$$

Both the overturn safety ratio (Expression (2)) and the natural frequency (Expression (4)) are the reverse-proportion to the block size. This result explains the reason why the block size does not influence the relation between safety ratio and dominant frequency.

The bonded part of block and base can be modeled in figure 28. When the bonding length and the tilt angle when the block falling is expressed as l_c and θ_C respectively, the maximum resistance moment M_r is given by Eexpression (5) and the tensile strength of bonded part is given by Expression (6).

$$M_r = \int_0^l y \cdot pSdy = \frac{E\theta_C S l_C^{\;3}}{3d} = MgL \qquad (5)$$

$$t_u = E \cdot \frac{l_C \cdot \theta_C}{d} \qquad (6)$$

Then the natural frequency f_c when the block falling is given by Expression (7).

$$f_C = \frac{1}{2\pi}\sqrt{\frac{ES}{3dML^2}\left(\frac{3MgL}{St_u}\right)^{\frac{3}{2}}} = \frac{1}{2\pi}\sqrt{\frac{3^{\frac{1}{2}} g^{\frac{3}{2}} \cdot E \cdot M^{\frac{1}{2}} \cdot}{t_u^{\frac{3}{2}} \cdot d \cdot S^{\frac{1}{2}} \cdot L^2}} \qquad (7)$$

Expression(7) explains the f_c is proportional to physical properties in the bonded part $((E/t_u^{3/2})^{1/2})$ and is low dependence on the block size.

4.4. Proposal of a quantitative evaluation method

Finally, we propose the concept of the quantitative evaluation method based on the safety ratio - dominant frequency nomogram. Figure 29 is a conceptual diagram of the nomogram. Many safety ratio-dominant frequency curves of various rock properties are as shown in the nomogram. By using this nomogram, the overturn safety ratio of a rock block can be estimated by the remotely measured dominant frequency and the physical properties of the rock estimated by sample examination.
Figure 30 shows the example of the data analysis and the stability evaluation of a rock block by the prototype system. Although a practicable nomogram has not been developed yet, we are intended to continue the study until establishing useful method for rock slope stability.

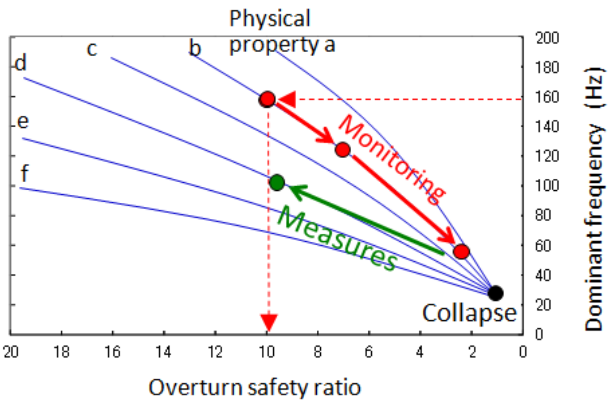

Figure 29. Conceptual diagram of the safety ratio – dominant frequency nomogram

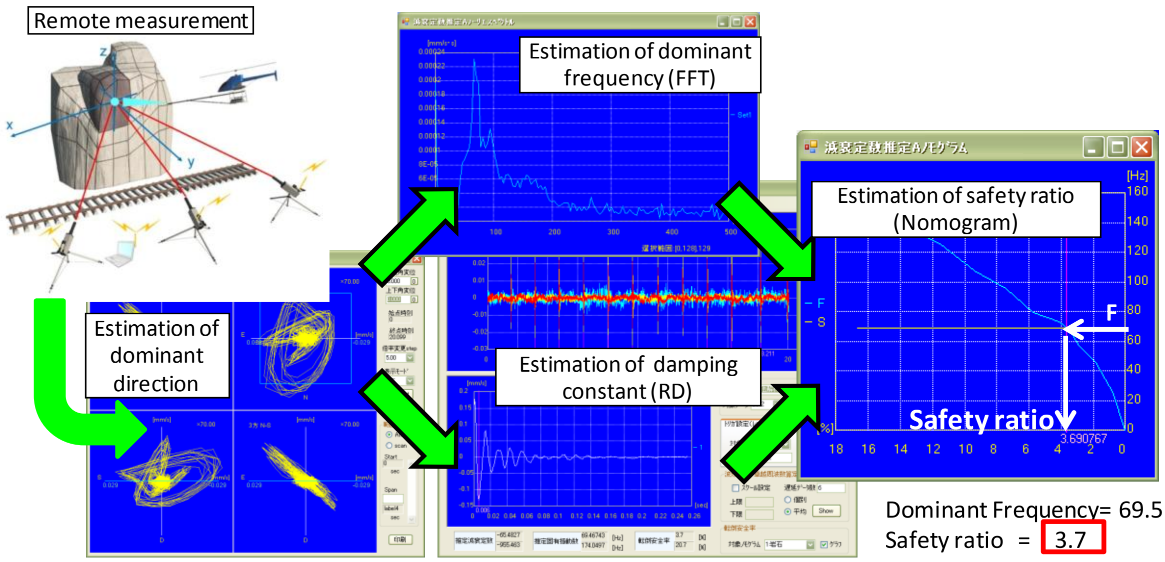

Figure 30. Example of the data analysis and the stability evaluation of a rock block by the prototype system

5. CONCLUSIONS

In order to prevent the rock fall damage to the railway due to an earthquake, we developed the rock slope stability investigation system by applying remote vibration measurement technique.

1) The 3D remote vibration measurement system for rock slope was developed using the LDV sensors and wireless LAN. The efficiency of the system was confirmed by laboratory experiments and field experiments.
2) The high performance reflective paint was developed that can improve the laser retro-reflectivity of rock surface. As the remote control system to form the reflective targets on a distant rock slope, the RC helicopter was developed that mounted the reflective paint spray device and the attitude control system.
3) We executed the model experiments by using concrete blocks bonded to the concrete base with a different adhesion condition. The quantitative relation was clarified between the mechanical stability and dominant frequency of rock block, and adequacy of the relation was confirmed by the numerical analysis and theoretical analysis.
4) A new method of rock stability evaluation was proposed based on the “Safety ratio - dominant frequency nomogram.”

We plan to investigate the influence on the rock block stability of seismic ground motions in the future.

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