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FUNDAMENTAL STUDY ON EVALUATING ROCK SLOPE STABILITY BY VIBRATION MEASUREMENTS USING REMOTE VIBRATION MEASURING SYSTEM

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Abstract. *The purpose of this study is to clarify the relationship between the mechanical stability of rock brock and its vibration characteristics so as to propose a new method of rock stability evaluation by measuring the vibration of rocks using remote vibration measuring system. Preventing rockfall damages to railway caused by earthquake and other reasons is becoming important, and thus early detection methods for unstable rock blocks are necessary. Therefore, a new method of safe and efficient rock stability evaluation using remote vibration measurement system is needed. In this study, we executed model experiments using concrete blocks bound to the concrete base unit under different adhesion conditions using Laser Doppler Velocimeter (LDV). Through these experiments, quantitative relation between the mechanical stability and the dominant frequency of rock block vibration was clarified. In addition, we executed a numerical analysis using FEM and the relationship was confirmed by the analysis. From the results of the experiment and the analysis, we investigated the relationship between the overturn safety factor, which is defined as the ratio of overturning moment to the maximum resistance moment of the block, and the dominant frequency of the rock vibration, and proposed a new method of rock stability evaluation using this relationship. We also executed a numerical analysis of the relation between the mechanical stability and the dominant frequency of rock block vibration under the influence of seismic ground motion. From the results, we have evaluated the mechanical stability of the rock under the influence of earthquakes by calculating the safety factor.*

1 INTRODUCTION

In Japan, there are many railway lines running through the mountainous areas. On such lines, train accidents and suspending operation caused by falling rocks often have occurred. Currently in Japan, rockfall inspection is carried out mainly by the visual inspection. However, some rockfalls is caused by invisible crack propagation; so it is difficult to evaluate the stability of rock block only by the visual inspection. In order to prevent the falling rocks along the route and ensure the safety and reliability of railway transportation, safe and efficient methods for evaluating the risk of falling rocks quantitatively are required.

Recently, some techniques for evaluating stability of rock block by means of measuring its vibration characteristics such as predominant frequency have been developed[1]. However, these methods require rock vibration measurements by sensors attached to the rock and thus have a problem in the safety and efficiency of the evaluation work. In such circumstances, we introduced a method of evaluating the risk of falling rocks by measuring the vibrational characteristics of the rocks using ”U-doppler”(Figure 2) which is a system developed by improving non-contact Laser Doppler Velocimeter (LDV)[2][3]. U-doppler is a long-distance non-contact vibration measuring system for the diagnosis of railway structures. U-doppler offers enhanced safety and efficiency for use in the field[4][5].

The purpose of this study is to clarify the relationship between the mechanical stability and vibration characteristics of rocks and propose a new method of rock stability evaluation by measuring the vibration of rocks using remote vibration measuring system.

In this study, we executed model experiments using concrete blocks bound to the concrete base unit under different adhesion conditions simulating the unstable rock. The dominant frequency of the concrete block vibration were measured using Laser Doppler Velocimeter (LDV) during the experiment. Through these experiments, we investigated the relationship between the mechanical stability of the concrete block and its dominant frequency using ”overturn safety factor.” Overturn safety factor is defined as the ratio of overturning moment to the maximum resistance moment of the block.

In addition, we executed a numerical analysis using FEM and the relation was confirmed by the analysis. Through the analysis, a similar relationship between the overturn safety factor and dominant frequency of rock block vibration was observed. We also executed a numerical analysis of the relation between the mechanical stability and the dominant frequency of rock block vibration under the influence of seismic ground motion. Based on the results, we have evaluated the mechanical stability of the rock under the influence of earthquakes by calculating the overturn safety factor.

Figure 1: Example of falling rock accident

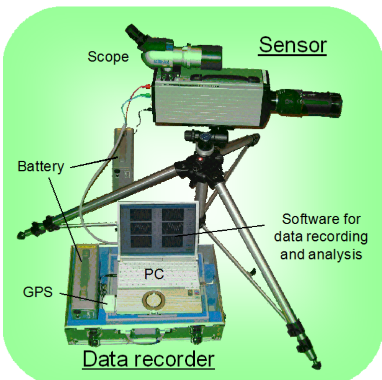


Figure 2: U-doppler

2 EXPERIMENT

In this section, we explain the model experiments executed using concrete blocks bound to the concrete base unit under different adhesion conditions simulating the unstable rock blocks. Through this experiment, dominant frequencies of concrete block were measured using LDV and the relationship between the mechanical stability and the dominant frequency of concrete blocks was clarified.

2.1 Experimental model

In this experiment, the relationship between the mechanical stability and the vibration characteristics of rocks was clarified using concrete block models which simulate the unstable rock. Figure 3 shows the state of experiments and Figure 4 shows the size of the whole model. From this subsection, the right-hand coordinate system shown in Figure 4 is used. The y-axis is defined as the direction of the back of the Figure 4.

The base unit and the block part are made of concrete and the bonding area of the block and the base unit is made of gypsum. In this experiment, we used 2 types of gypsum, ”Hi-stone” and ”Grade A gypsum”. These are product names of the gypsum manufacturer, *Yoshino Gypsum Co.,Ltd.* Table 1 shows the material properties used in this experiment.

In the experiment, three different sizes of concrete block were used. Table 2 shows the sizes of concrete blocks used in the experiment.

Figure 3: State of experiment

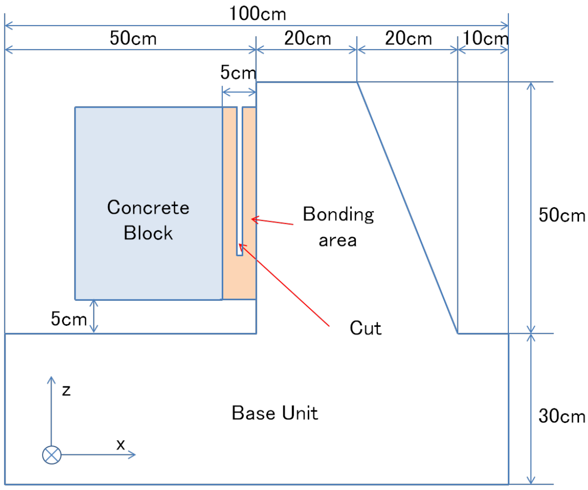
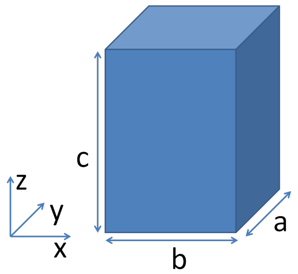


Figure 4: Size of experimental model

Material name	Concrete	Hi-stone	Grade A gypsum
Density(kg/m^3)	2100	1657	1538
Young’s modulus(MN/m^2)	22000	7800	2290
Poisson’s ratio	0.2	0.23	0.2
Tensile strength (MN/m^2)		2.91	0.849

Table 1: Material properties.



Block size	a(cm)	b(cm)	c(cm)	Mass(kg)
Large	20	30	40	57.6
Medium	15	22.5	30	24.3
Small	10	15	20	7.2

Table 2: Sizes of concrete blocks

2.2 Experiment method

In this experiment, the concrete block and the base unit were connected by gypsum part. We simulated the instability of the rock by making a cut in this gypsum part with a saw gradually and the bonding length of the concrete block and the base unit was adjusted. For each bonding length, the velocity of the concrete block was recorded with LDV until the concrete block fell. The velocity was recorded when vibrating the concrete base unit and the ground. The velocity of the concrete block by micro-tremors was also recorded. The dominant frequency was obtained by the Fourier transform of the recorded velocity waveform. This operation was repeated until the concrete block fell.

2.3 Result of the experiment

Figure 5 shows the relationship between the bonding length and the dominant frequency.

From Figure 5, the relationship between the bonding length and the dominant frequency could be approximated by a line. For gypsum with higher Young's modulus, gradient of the approximate line became greater. For the same type of gypsum, the gradient of the approximate line becomes smaller as the size of block is larger. For the same bonding length, the larger block has the smaller dominant frequency.

In the experiment, two types of destruction state were observed at the bonding area. One was observed on the extension of the cut made by a saw. For the other, crack extended horizontally from the tip of the cut made by the saw and the bonding area peeled off from the base unit. This

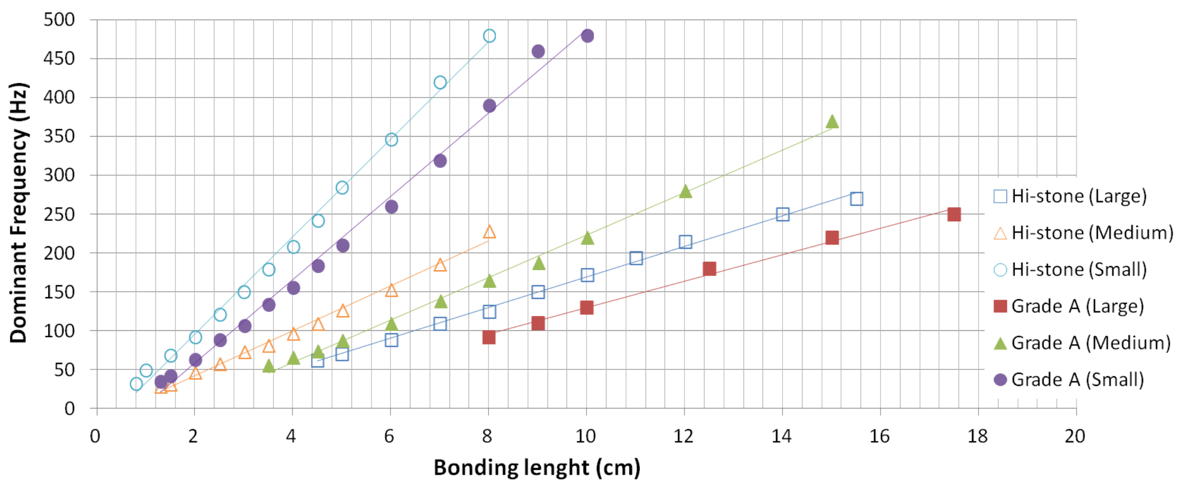
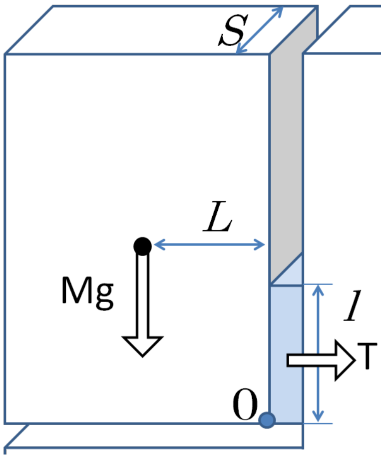


Figure 5: Relationship between the dominant frequency and the bonding length

type of destruction seems to occur only in model experiment.

In order to clarify the relationship between the dominant frequency and the stability of the concrete block, we introduced a parameter called "overturn safety factor". The overturn safety factor is defined as the ratio of overturning moment to the maximum resistance moment of the block. The lower-right corner of the block is considered as the rotation center of these moments. The gypsum is considered to be broken when a value of the overturn safety factor becomes less than 1. Figure 6 shows the idea of the overturn safety factor.



$$F = \frac{T}{(Mg \times L)/2} = \frac{(P \times l^2 \times S)/2}{(Mg \times L)/2}$$

F : Overturn safety factor
T : Total tensile strength
M : Mass of concrete block
g : Gravity
L : Distance to centroid of block
P : Tensile strength
l : Bonding length
S : Width of brock and bonding area
O : Center of rotation

Figure 6: Overturn safety factor

Before calculating the overturn safety factor, the tensile strength of each material was back-calculated for each block size on the assumption that the bonding area is destructed when the overturn safety factor is equal to 1. As the result, the back-calculated tensile strength is shown to be $1/2$ to $3/4$ of the tensile strength by laboratory tests. Therefore, when calculating the overturn safety factor, the $2/3$ of the tensile strength determined by the laboratory test is used. Figure 7 shows the summarized relationship between the dominant frequency and the overturn safety factor.

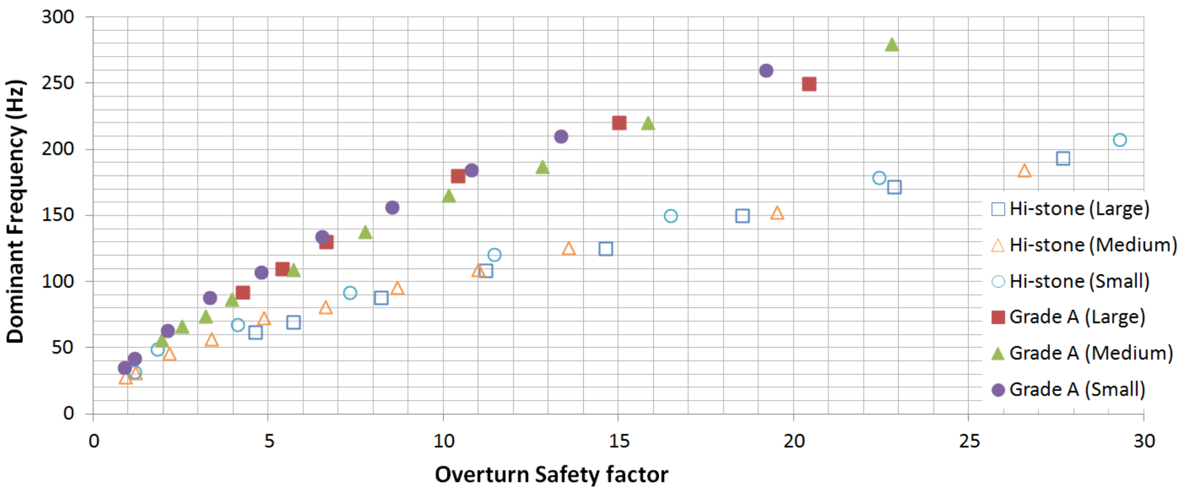


Figure 7: Relationship between the dominant frequency and overturn safety factor (Experiment)

From this figure, regardless of the size of the block, the relationship between the dominant frequency and overturn safety factor is able to be approximated by a single curve for each type of material. This indicates that if the tensile strength of the rock is known, the overturn safety factor can determined by measuring the dominant frequency of the rock.

3 NUMERICAL ANALYSIS

In this section, we explain the analysis using FEM executed corresponding to the experiment mentioned in the section 2. Two types of analyses were performed. The first analysis is eigenvalue analysis. The frequency of the first mode of vibration of blocks was calculated for each bonding length in this analysis. From this analysis, the relationship between the dominant frequency and the mechanical stability of the concrete block was discussed. The second analysis is dynamic analysis under seismic conditions. From this analysis, effects of ground motion on concrete block was evaluated. For both the analyses, structural analysis software ”LS-DYNA” was used.

3.1 Analysis model

The analysis model was constructed with the objective to execute comparison between the analysis results and the results by the experiments. Figure 8 shows the model used in the analysis. In the experiment, the bonding length was adjusted by making a cut into gypsum with a saw. In the analysis, this was modeled as a gap with 2mm width. The base unit, concrete block, and bonding area were modeled as elastic bodies with hexahedral solid elements. For the bonding area, the two types of material, Hi-stone and Grade A gypsum, were also used. Material properties of concrete and gypsum used in the analysis were the same as those used in the experiment.

In the experiment, the base unit was long in the y-axis direction. However, compared with the concrete block, the vibration amplitude of the base unit was considered to be very small, and its dominant frequency is much higher. Furthermore, modeling the whole base unit significantly increases the number of elements. Therefore, the base unit was modeled only for the same length as the concrete block in the y-axis direction, and the bottom surface and the surface in the y-axis direction were fixed.

3.2 Eigenvalue analysis

The dominant frequency of the concrete block vibration for each bonding length was solved through the eigenvalue analysis. In the experiment, especially in shorter bonding length, on;y one clear peak had appeared in spectrum of the velocity of concrete block. Therefore, in the experiment, the dominant vibration of the block is mainly due to the first mode of vibration. The first mode of vibration is rotation around lower-right corner of the block. Figure 9 shows the first mode of concrete block vibration.

In the analysis, three different sizes of concrete block(large, medium, small) and two types of gypsum (Hi-stone and Grade A gypsum) were used. Sizes of concrete blocks used in the analysis were the same as those used in the experiment. For these 6 cases, eigenvalue for each bonding length was calculated.

The dominant frequencies of concrete blocks calculated in the analysis were compared with the dominant frequencies of concrete blocks obtained in the experiment. In Figure 10, relationships between the bonding length and dominant frequency obtained by the analysis are compared with those obtained by the experiment.

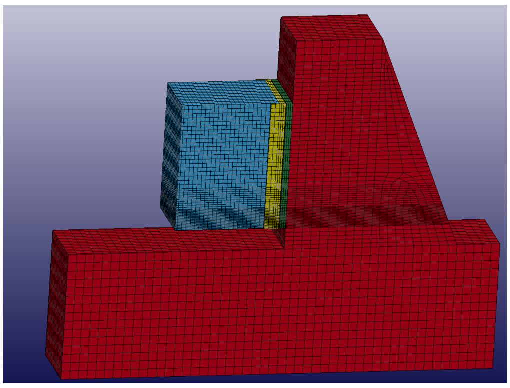


Figure 8: Analysis model

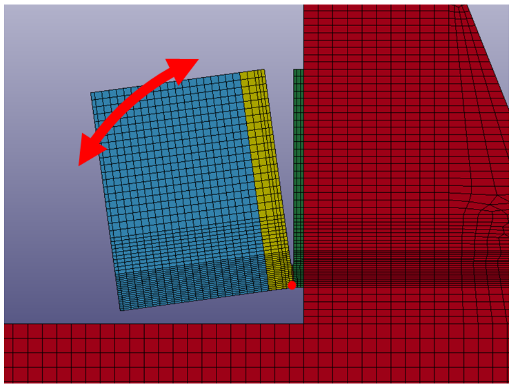
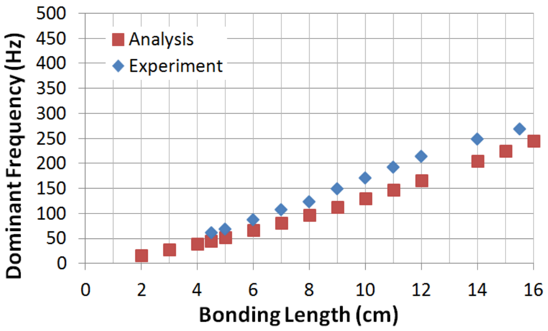
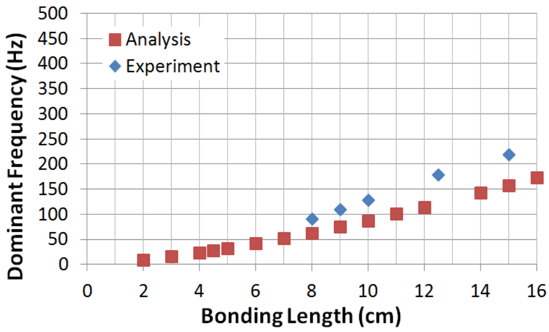


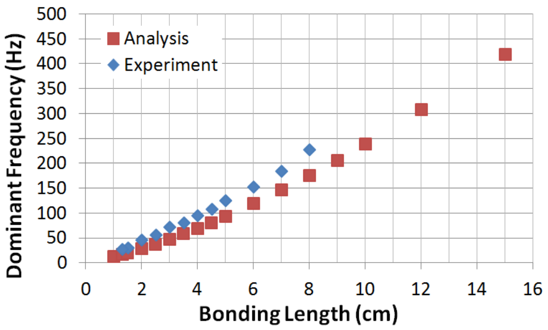
Figure 9: First mode of concrete block’s vibration



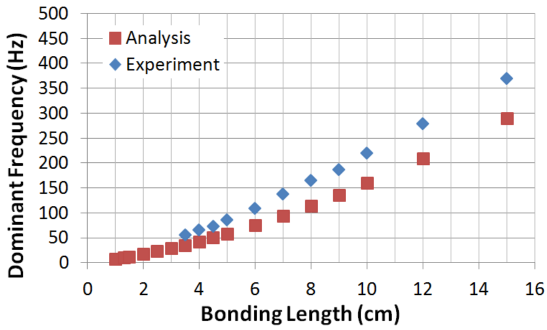
(a) Hi-stone (Large)



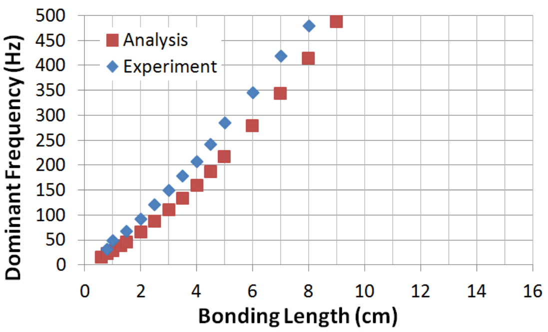
(b) Grade A gypsum (Large)



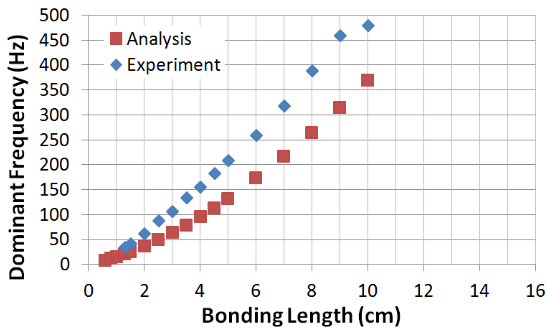
(c) Hi-stone (Medium)



(d) Grade A gypsum (Medium)



(e) Hi-stone (Small)



(d) Grade A gypsum (Small)

Figure 10: Comparison of relationships between the bonding length and dominant frequency

In Figure 10, dominant frequencies solved by the analysis show lower values than those obtained by the experiment in all cases. However, the tendency that the dominant frequency becomes lower as the bonding length becomes shorter which implies the increase of instability of concrete block is observed in both the experiment and the analysis. Similarly to the experiment, a larger block has a smaller dominant frequency for a given bonding length.

In the experiment, the relationship between bonding length and dominant frequency can be approximately linear. On the other hand, a quadratic function curve is in good agreement with the result of analysis. The dominant frequency was solved as the first mode of vibration in the analysis. However in the experiment, especially in the longer bonding length, the concrete block vibration might be influenced by other modes of vibrations; this might cause the different approximate curves for the analysis and for the experiment respectively.

The relationship between the dominant frequency and the overturn safety factor was summarized for the analysis in the same way as for the experiment. Figure 11 shows the relationship between the dominant frequency and overturn safety in analysis. When calculating the overturn safety factor, $2/3$ of the tensile strength of gypsum determined by the laboratory test was used as adhesive force.

Similar results were obtained from both the experiment and the analysis. The relationship between overturn safety factor and dominant frequency is able to be approximated by a single curve for each material regardless of the size of the block. From Figure 11, when the overturn safety factor is 1, the dominant frequency of Hi-stone is approximately 19Hz and dominant frequency of Grade A gypsum is approximately 23Hz by the analysis. On the other hand, from Figure 7, the dominant frequency of Hi-stone is approximately 30Hz and dominant frequency of Grade A gypsum is approximately 35Hz in by the experiment when the overturn safety factor is 1.

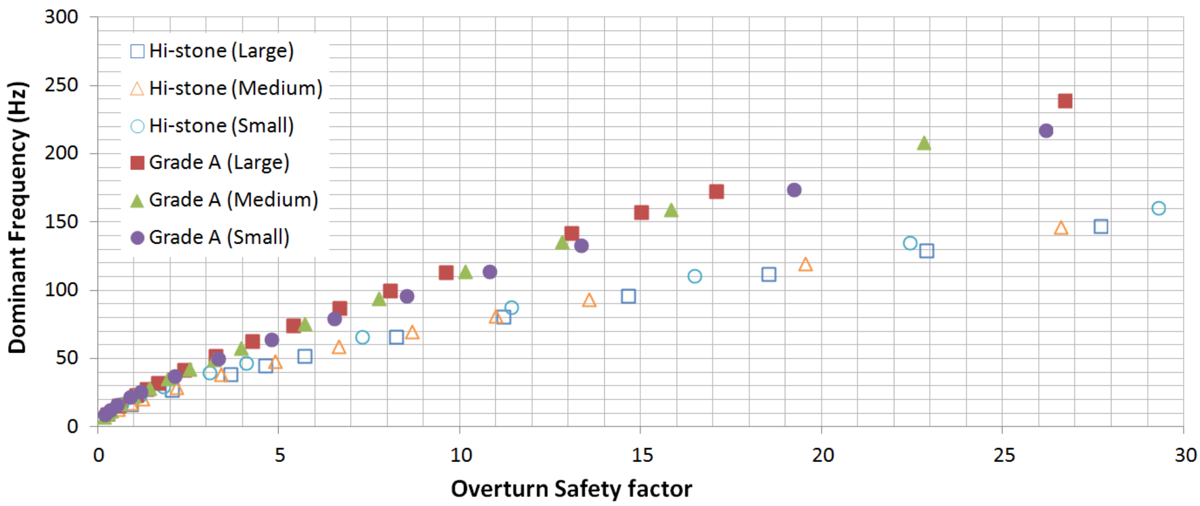


Figure 11: Relationship between dominant frequency and overturn safety factor (Numerical analysis)

3.3 Analysis under the influence of seismic ground motion

In this section, a numerical analysis under the influence of seismic ground motions was executed. The same analytical model as the one used in the subsection 3.2 was also used in the analysis.

In the seismic ground motion analysis, three types of ground motion were applied to the model. Figures 12 to 14 show the waveforms of ground motions applied in the analysis.

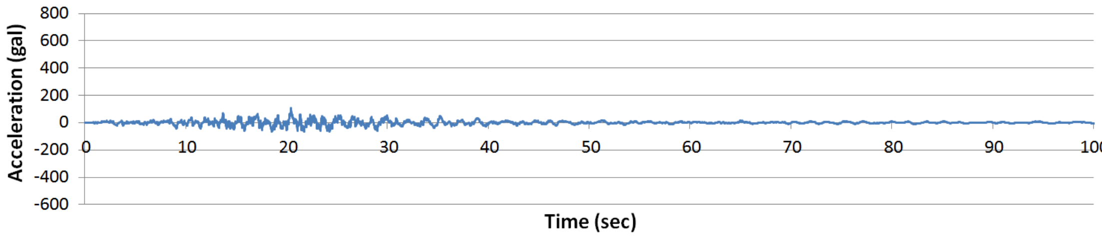


Figure 12: Ground motion No.1 (Level 1 earthquake ground motions)

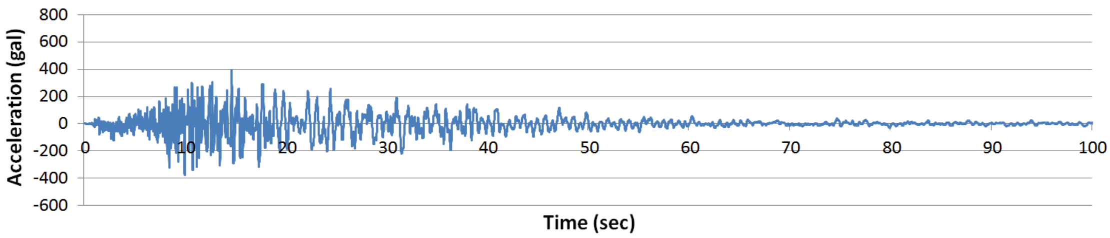


Figure 13: Ground motion No.2 (Level 2 earthquake ground motions by trench type earthquake)

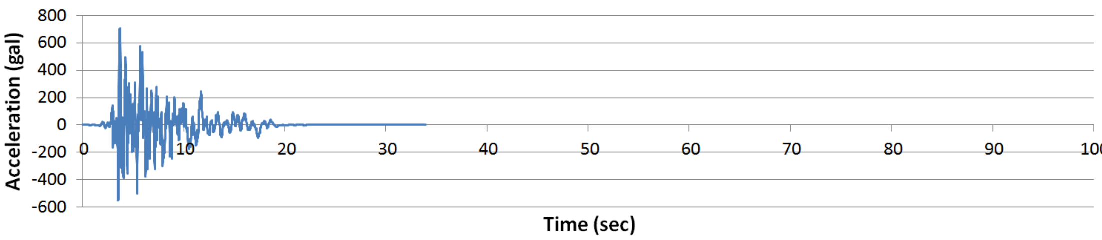


Figure 14: Ground motion No.3 (Level 2 earthquake ground motions by dislocation earthquake)

Waveform in Figure 12 is the waveform of ground motion No.1. This waveform is a type of Level 1 earthquake ground motion. Japanese seismic criterion defines Level 1 earthquake ground motion as an earthquake ground motion that is more likely to occur during the designed working life of facilities. Waveform in Figure 13 is the waveform of ground motion No.2. This waveform is a type of Level 2 earthquake ground motion caused by trench type earthquake. Japanese seismic criterion defines Level 2 earthquake ground motion as the largest earthquake ground motion that can occur the during designed working life of facilities. Waveform in Figure 14 is the waveform of ground motion No.3. This waveform is a type of Level 2 earthquake ground motion caused by dislocation earthquake.

In this analysis, effect on stability of concrete block under the ground motion was evaluated using the stress generated in the bonding area. It is thought that the destruction of the bonding area occurs when tensile force of the bonding area exceeds tensile strength. From the experiment, concrete blocks seemed to vibrate around the lower-right corner of the block. Therefore, it is considered that if the maximum x-axis stress of the bonding area reaches tensile strength, the bonding area destructs.

Before executing the ground motion analysis, the static analysis considering the dead load was executed. From this analysis, stress due to the concrete block's dead load in the bonding area was calculated. This analysis was executed for each bonding length using the implicit method.

From the result of the static analysis, the maximum stress of the bonding area in the analysis largely exceeded the tensile strength which was determined by the laboratory test even for the bonding length for which the bonding area was not destructed in the experiment. Due to this, we interpolate the relationship between the result of the static analysis and the overturn safety factor with piecewise linear functions. From this, the maximum x-axis stress of the bounding area when the overturn safety factor is equal to 1 was obtained. We considered this maximum stress as the criterion of whether bonding area destructs or not. If a maximum x-axis stress observed in the ground motion analysis exceeds this value, we regard the bonding area as destructed. Figure 15 shows the relationship between the maximum x-axis stress of the bonding area and the overturn safety factor.

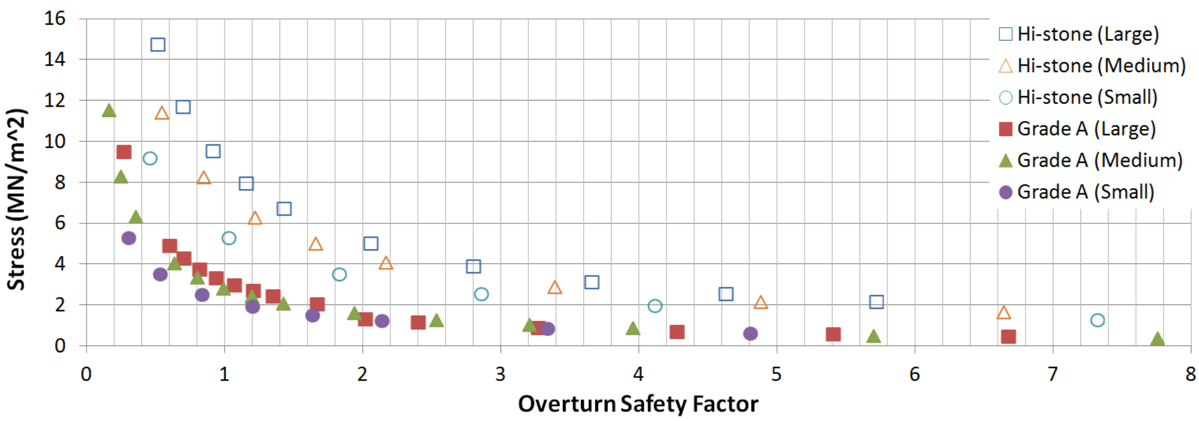


Figure 15: Relationship between the maximum x-axis stress of the bonding area and the overturn safety factor

For each block size and bonding length, the maximum x-axis stress generated in the bonding area was calculated under these three types of ground motion in the analysis. From the result of static analysis and ground motion analysis, the bonding length when bounding area destructs under the effect of each ground motion was obtained by piecewise linear interpolation of the result of the analysis. After that, the overturn safety factor corresponding to the bonding area destructs under each ground motion was calculated.

Table 3 and Table 4 show the boding length and overturn safety factor corresponding to destruction of the bonding area for each ground motion analysis. To clarify the effect of ground motions, we compared result of the ground motion analysis with the eigenvalue analysis. Figure 16 shows the relationship between the overturn safety factor and the dominant frequency with the results of the ground motion analysis shown in Table 3 and Table 4. The relationship between the results of eigenvalue analyses and overturn safety factor are also shown in Figure 16.

Form the result of the analysis, effect of the ground motion No.3 (Level 2 earthquake ground motion by dislocation earthquake) was the largest. For each material, the bonding area destructs at almost the same value of overturn safety factor regardless of the block size. For models whose bonding area is made of high stone, the bonding area is destructed even at the value of overturn safety factor of about 2.3 under the influence of ground motion No.3. Similarly, for models

Material	Block	Ground motion		
		No.1	No.2	No.3
Hi-stone	L	2.3cm	2.7cm	3.2cm
	M	1.5cm	1.7cm	2.1cm
	S	0.8cm	0.9cm	1.2cm
Grade A	L	4.1cm	4.8cm	5.2cm
	M	2.7cm	3.2cm	3.6cm
	S	1.5cm	1.7cm	2.0cm

Table 3: Bounding length

Material	Block	Ground motion		
		No.1	No.2	No.3
Hi-stone	L	1.17	1.70	2.28
	M	1.17	1.66	2.32
	S	1.22	1.73	2.44
Grade A	L	1.15	1.56	1.83
	M	1.16	1.61	2.06
	S	1.15	1.60	2.13

Table 4: Overturn safety factor

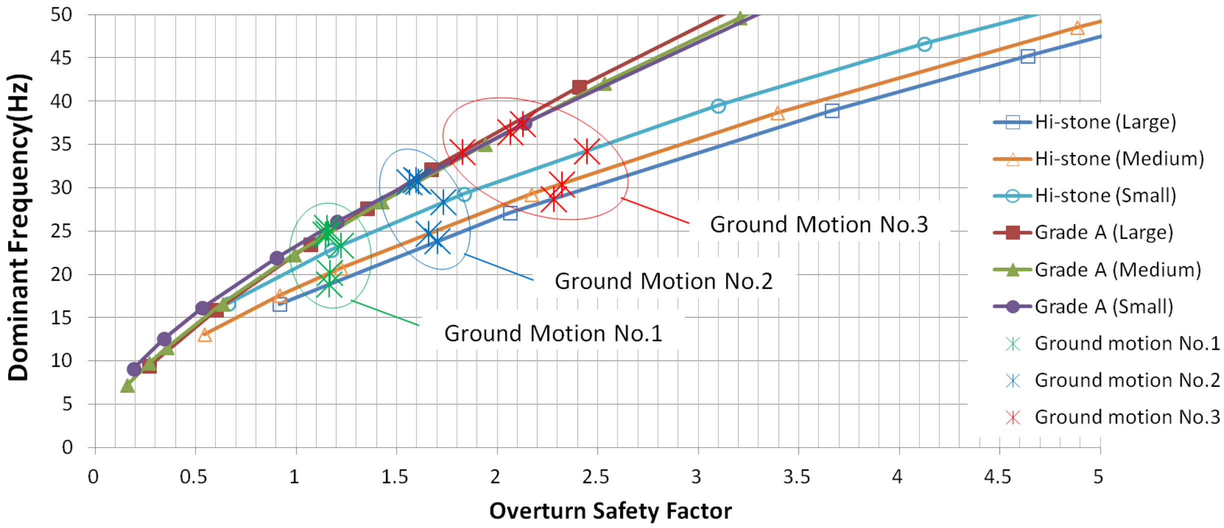


Figure 16: Effects of ground motion

whose bonding area is made of Grade A gypsum, the bonding area is destructed even at the value of overturn safety factor of about 2.0 under the influence of ground motion No.3

From these results, it is expected that if material property and overturn safety factor of a rock are known, it is possible to determine whether a rock collapses or not by a given earthquake. However, only 2 types of bonding area's material and 3 different sizes of blocks were used in this experiment and analysis. In the future, it is necessary to examine effects of bonding area's material and block size by testing more different types of materials and sizes of the blocks.

4 CONCLUSIONS

- The relationship between the dominant frequency and the overturn safety factor is able to be approximated by a single curve for each material regardless of the sizes of the blocks in the experiment. This indicates that the overturn safety factor can be determined by measuring the dominant frequency of the rock if the tensile strength of the rock is known.

- Similar relationships between the overturn safety factor and the dominant frequency are observed in the experiment and in the analysis. However, the dominant frequencies observed in the analysis are lower than those observed in the experiment. It is necessary to determine the cause of this difference by evaluating the adhesive strength more adequately and by introducing more appropriate modeling of bonding area.

- If the material property and the overturn safety factor of a rock are known, it is possible to determine whether a rock collapses or not by a given earthquake from the result of the ground motion analysis.
- A simple method was used to calculate the moment of resistance in calculating the overturn safety factor. Moreover, 2/3 of the tensile strength was used to calculate the overturn safety factor. It is necessary to determine the stress distribution or deformation of the bonding area and to introduce appropriate method in order to evaluate the tensile force and the rock stability in the future.
- In this study, only 2 types of bonding area's materials and 3 different sizes of blocks were used in the experiment and the analysis. In the future, it is necessary to examine effects of bonding area's material and block size by testing more different types of materials and sizes of the blocks.

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REFERENCES

[1] K. Ogata, H. Matsuyama, K. Amano, Evaluation of the rockfall potential utilizing the characteristics if vibration. *Journal of Japan society of Civil Engineers*, **VI-61,** 123-135, 2003. [In Japanese]

[2] O. Murata, F. Uehan, H. Saito, G. C. Ma, Fundamental Study on the Evaluation Method of Mechanical Stability of Rock Blocks by Remote Vibration Measurement. *RTRI report,* **Vol.25, No. 2**, 47-52, 2011. [In Japanese]

[3] F. Uehan, H. Saito, G. C. Ma, Fundamental Study on the Remote Vibration MeasuringSystem for Evaluating Rock Slope Stability. *The 15th World Conference on Earthquake Engineering (15 WCEE),* 2012.

[4] F. Uehan, O. Murata, H. Saito, Y. Ohtsuka, Fundamental study on the remote vibration measuring system for evaluating rock slope stability. *RTRI Report,* **Vol. 24, No. 4,** 5-10, 2010. [in Japanese]

[5] F. Uehan, Development of non-contact vibration measuring system for inspection of seismic damage to railway structures. *The 14th World Conference on Earthquake Engineering (14 WCEE),* 2008.