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Experimental study on seismic stability of foundation rocks under critical facilities

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ABSTRACT: A dynamic centrifugal model test was performed to assess the seismic stability of foundation rocks and thereby demonstrate the viability of evaluating seismic stability using ground displacement. The test results demonstrated that the slip safety factor in the vibration step, where considerable residual displacement was observed during the model test, was less than one. In addition, conventional evaluation methods were found to be conservative. Furthermore, the progression of ductile failure was observed in the foundation-rock model although the slip safety factor was less than one. Based on the study results, procedures were proposed for evaluating seismic stability using ground displacement.

1 INTRODUCTION

The occurrence of fatal, large-magnitude earthquakes in the recent past has led to increased attention being focused on the consideration of earthquake ground motion during the design phase of modern structures. Accordingly, the quantitative assessment of the seismic resistance of critical facilities to the earthquake-induced failure of the foundation rock has become important.

In Japan, the seismic stability of foundation rocks has conventionally been evaluated in terms of their bearing capacity, inclination, and sliding (JEAG4601-1987, 1987). In terms of the sliding motion during an earthquake, a slip safety factor based on an equivalent linear analysis is conventionally used to evaluate the stability of foundation rocks. However, a slip-safety-factor value of less than one does not necessarily indicate immediate ground instability. Therefore, the evaluation of seismic stability based on ground displacement is considered to be a more effective approach (Kawai et al., 2017).

The present paper describes a dynamic centrifugal model test to evaluate the seismic stability of foundation rocks. Further, the applicability of conventional slip-safety-factor evaluation methods is verified. Finally, based on the experimental results, procedures are proposed for evaluating the seismic stability based on ground displacement.

2 EXPERIMENTAL CONDITIONS

In the centrifugal model test, the actual stress state could be reproduced by loading a 1:N downscaled model with a gravity force (centrifugal force) multiplied by N. A foundation-rock model with a reduction ratio of 1:50 was constructed using artificial-rock materials and weak layers. Vibration tests were performed in a centrifugal force field under a centrifugal acceleration of 50 g.

2.1 *Foundation-rock model*

The foundation-rock model and instrument arrangement are shown in Figure 1. The model was 200 mm (10 m upon real-scale conversion) in height and 300 mm in depth. On the boundary surfaces, cutouts measuring 100 × 100 mm were provided to avoid interference with the rigid box. The building model dimensions were 60 (width) ×40 (height) mm (3 ×2 m upon real-scale conversion), and the density of the building material was 1,200 kg/m^3.

Measured variables included accelerations produced under as well as on the ground surface along with corresponding displacements induced in the building model and on the ground surface. A relative displacement gauge was installed at a position straddling the weak layer. For comparison, a second relative displacement gauge was installed on

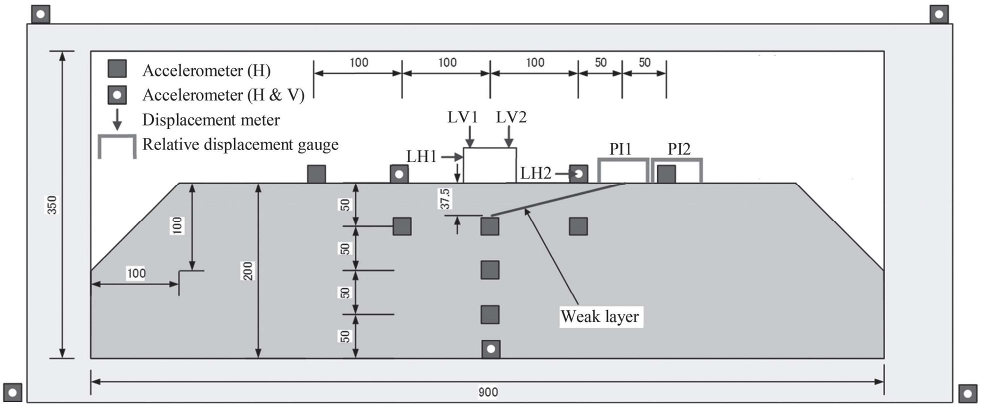


Figure 1. Foundation-rock model and instrument arrangement.

Table 1. Physical properties of artificial-rock materials and weak layer (σ_m: mean stress).

	Rock	Weak layer
Unit weight	20.3 kN/m³	20.6 kN/m³
Peak shear strength	$C_p = 267.1$ kN/m² $\varphi_p = 34.7°$	$C_p = 0.0$ kN/m² $\varphi_p = 28.6°$
Residual shear strength	$a = 4.61$, $b = 0.70$ $(\tau_r = a \times \sigma_m^b)$	$C_r = 0.0$ kN/m² $\varphi_r = 19.3°$
Tensile strength	$\sigma_t = 41.4$ kN/m²	$\sigma_t = 0.0$ kN/m²
Initial elastic shear modulus	933000 kN/m²	2800 kN/m²
Poisson's ratio	0.42	0.49

the ground surface immediately adjacent to the weak layer.

2.2 *Properties of foundation-rock model*

Table 1 lists the physical properties of the materials used in the construction of the artificial-rock model and weak layer. The properties were obtained from various physical and mechanical tests.

2.2.1 *Properties of artificial-rock materials*

Because the physical properties of different natural rocks vary considerably, the foundation-rock model used in this study was created using cement-modified soil (with a curing period of 7 days). For a soil volume of approximately 1 m³, the formulation was 82 kg of high-early-strength Portland cement, 370 kg of distilled water, 817 kg of limestone crushed sand, 817 kg of limestone fine powder, and 1 kg of admixture. Figure 2 shows the stress–strain relationships obtained from plane-strain compression tests.

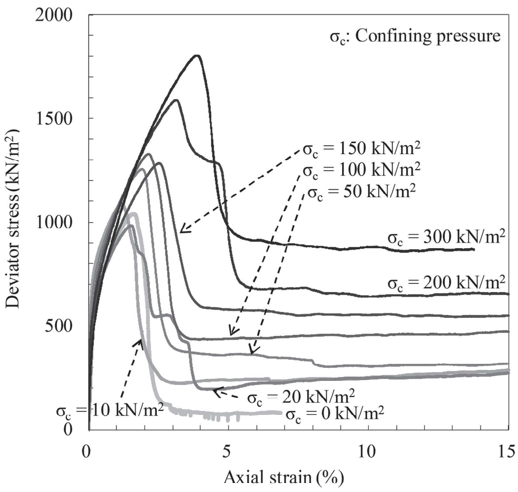
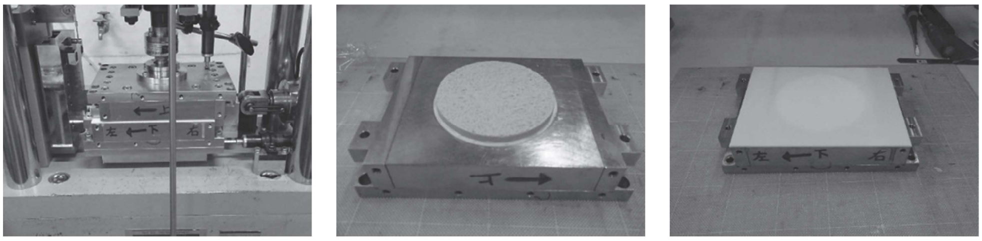


Figure 2. Stress–strain relationships obtained from plane-strain compression tests.

2.2.2 *Properties of artificial weak layer*

Based on the study performed by Ishimaru and Kawai (2011), the weak layer within the rock mass was reproduced by installing a 0.2-mm-thick Teflon sheet within the foundation-rock model prior to the commencement of hardening of the artificial-rock material. The resultant artificial weak layer had constant degrees of roughness, bite, etc. Further, through prior examination, the cohesion between the post-hardening artificial-rock material and Teflon sheet was confirmed to be very small. Therefore, under this condition, the shear resistance of the artificial weak layer can be considered to be equal to the frictional force generated between the artificial-rock material and Teflon sheet.



(a) Overall view of equipment. (b) Upper box: artificial rock. (c) Lower box: Teflon sheet.

Figure 3. Single-plane shearing test for examining frictional force generated between artificial rock material and Teflon sheet.

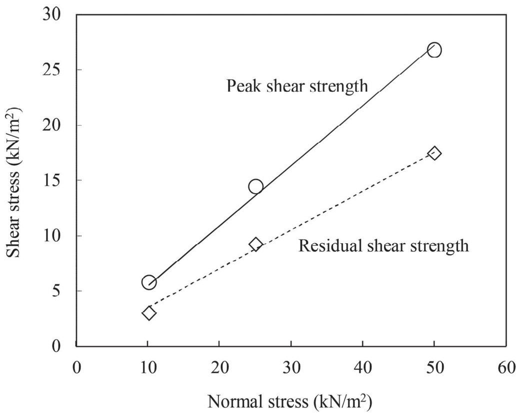
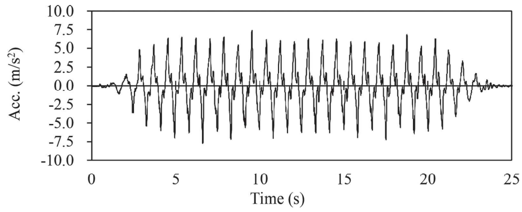
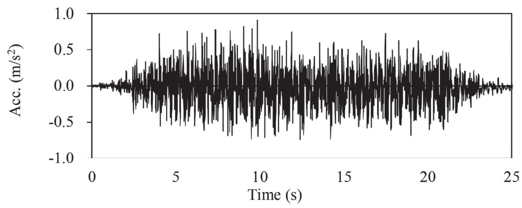


Figure 4. Shear stress–normal stress relationships obtained from single-plane shearing tests.



(a) Horizontal acceleration.



(b) Vertical acceleration.

Figure 5. Input acceleration (vibration step d04).

The frictional force generated between the artificial-rock material and Teflon sheet under normal-stress loading was examined by performing a single-plane shearing test (Figure 3). Figure 4 shows the test results; the maximum and residual shear resistances increase in proportion to the normal stress.

2.3 *Input acceleration*

Input acceleration was provided in the form of a sinusoidal wave with a wave number of 20 (frequencies of 1.2 and 1.6 Hz upon real-scale conversion) in the main part, and four tapers were provided before and after the main part. During the test, the acceleration amplitude was increased for each vibration step. Horizontal movement was provided as the only input. However, the vertical motion—considered to be caused by shaking table rocking—was also measured during vibration. Figure 5 shows the input acceleration of vibration step d04, and Table 2 lists the maximum acceleration amplitudes at different vibration steps. The table indicates that the 1.6-Hz excitation produces greater vertical motion than the 1.2-Hz excitation owing to the characteristics of the experimental apparatus.

Table 2. Maximum values of acceleration amplitude at different vibration steps.

Vibration step	Frequency	Horizontal acc. m/s^2	Vertical acc. m/s^2
d01	1.2	0.57	0.13
d02	1.2	3.47	0.42
d03	1.2	5.72	1.15
d04	1.2	7.77	0.91
d05	1.2	9.16	1.22
d06	1.2	10.40	1.50
d07	1.6	8.68	1.87
d08	1.6	10.04	2.88
d09	1.6	11.53	3.84
d10	1.6	11.25	3.39

3 TEST RESULTS

Figure 6 shows the accumulated values of the residual inclination of the building model at different vibration steps. Figure 7 shows the accumulated residual values of the horizontal displacements of the building model and ground at different vibration steps, and Figure 8 shows the accumulated residual values of the displacements measured by the relative displacement gauge at different vibration steps. These figures confirm that the amount of residual displacements rapidly increases after vibration step d09.

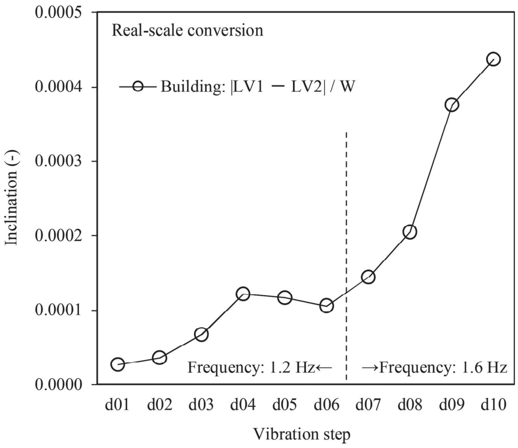


Figure 6. Accumulated values of residual inclination of building model at different vibration steps.

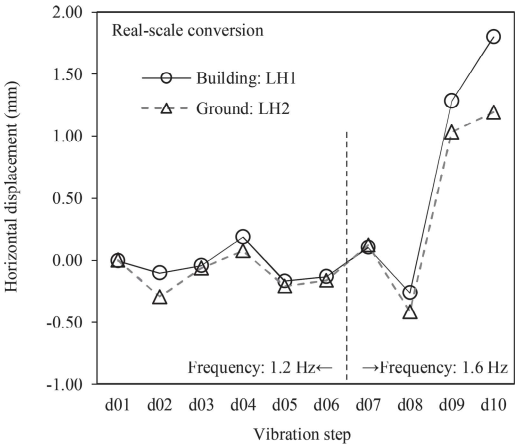


Figure 7. Accumulated residual values of amount of horizontal displacements of building model and ground at different vibration steps.

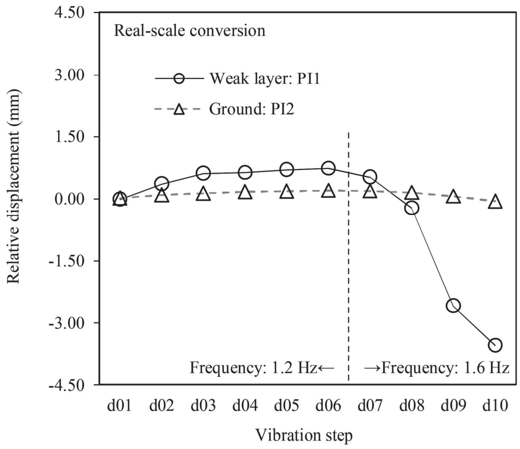


Figure 8. Accumulated residual values of amount of displacements obtained by relative displacement gauge at different vibration steps.

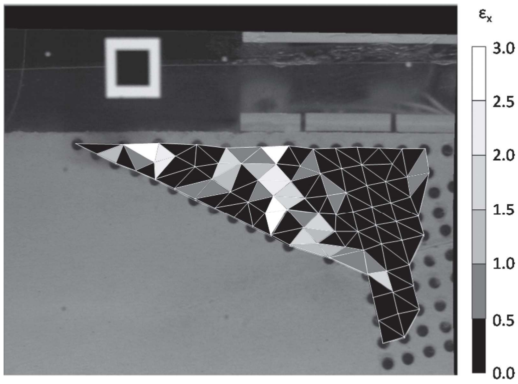


Figure 9. Horizontal strain distribution calculated from images taken by high-speed camera at vibration step d10.

Figure 9 shows the strain distribution calculated from images captured by a high-speed camera at vibration step d10. The figure confirms that cracks connecting the lower end of the weak layer and the left side of the building model are generated although it is not yet clear from images captured at vibration step d09. Owing to the occurrence of these cracks, the upper part of the weak layer is estimated to move.

4 EVALUATION OF SLIP SAFETY FACTOR

Considering the results obtained from the dynamic centrifugal model test, the applicability of the slip-safety-factor evaluation method based

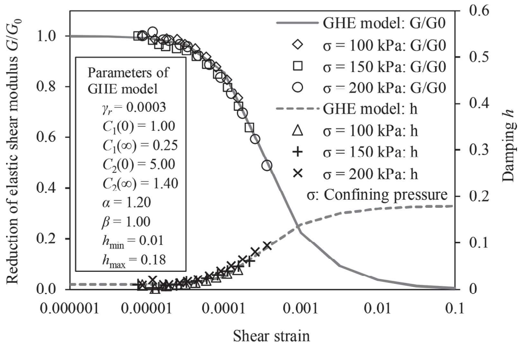


Figure 10. Dynamic deformation characteristics of artificial-rock material obtained from cyclic triaxial tests.

Table 3. Slip safety factors for different vibration steps.

Vibration step	Minimum slip safety factor		Slip safety factor obtained from model test
	Slip line		Slip line
d01	No. 6	24.78	24.78
d02	No. 6	8.38	8.38
d03	No. 5	5.10	5.61
d04	No. 4	3.02	3.33
d05	No. 1	2.12	2.67
d06	No. 6	1.40	1.40
d07	No. 6	1.76	1.76
d08	No. 3	0.86	0.98
d09	No. 2	0.39	0.72
d10	No. 2	0.20	0.45

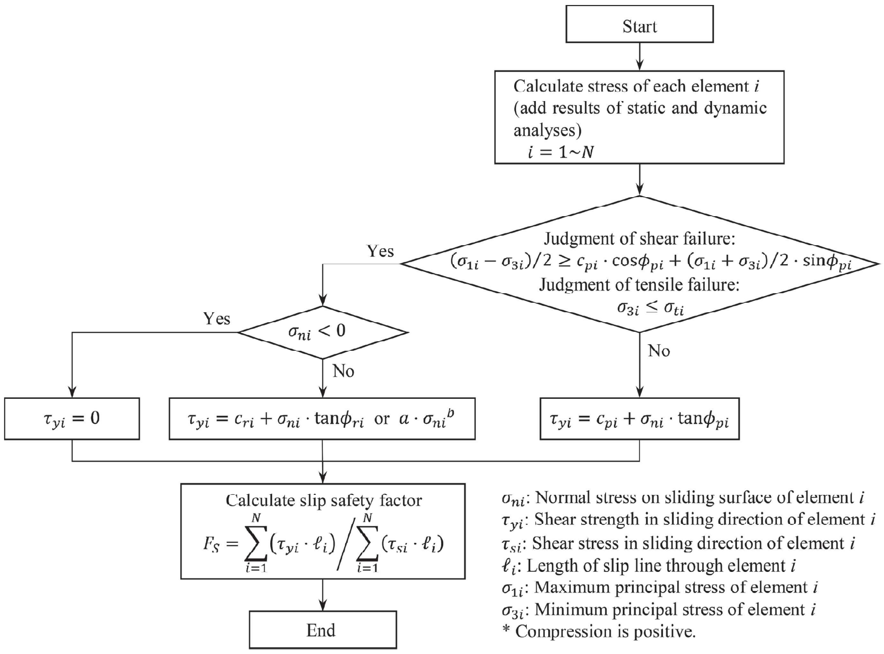


Figure 11. Flowchart for calculating slip safety factor.

on the equivalent linear analysis was verified. The properties of the foundation-rock model used for performing the equivalent linear analysis are listed in Table 1. The dynamic deformation characteristics of the artificial-rock material were set (Figure 10) using the general hyperbolic equation (GHE) model (Tatsuoka and Shibuya, 1992). On the other hand, the artificial weak layer was modeled to represent linear elastic-joint elements. The unit weight of the artificial weak layer was 20.6 kN/m^3, which was equal to that of the Teflon sheet, and the corresponding Poisson's ratio was 0.49 based on the assumption of no volume change. The pseudo shear modulus of elasticity, which was induced by modeling the artificial weak layer as linear elastic-joint elements, was set as 2,800 kN/m^2 from the gradient up to the maximum shear resistance during single-plane shearing tests.

Equivalent linear analyses were performed using the same input accelerogram as the one used in the centrifugal model test. The stresses used for calculating the slip safety factor were obtained by adding self-weight stresses and stresses induced during

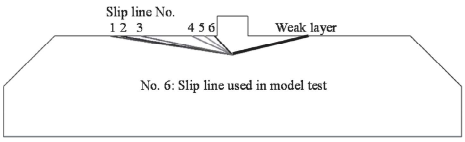


Figure 12. Slip line shapes for minimum slip safety factor.

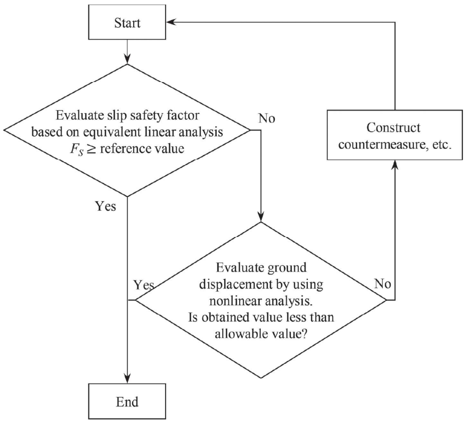


Figure 13. Flowchart for seismic stability evaluation of foundation rocks located under critical facilities.

an earthquake. Figure 11 shows the procedure for calculating the slip safety factor.

The values of the minimum slip safety factor measured during different vibration steps are listed in Table 3, and the slip-line shapes corresponding to these values of the slip safety factor are shown in Figure 12. The table indicates that the minimum slip safety factor is less than one after vibration step d08 although the residual displacement rapidly increases at vibration step d09 during the test. Therefore, the slip-safety-factor evaluation method can be considered to be conservative. Although the slip safety factor of the slip line generated during the tests does not represent its minimum value, it is similar to the minimum value in that it is less than one before the residual displacement rapidly increases. In addition, even if the slip safety factor is less than one, the amount of displacement that can be caused by sliding is limited. This indicates that in the event of an earthquake, foundation rocks do not spontaneously lose their seismic stability.

5 PROCEDURE FOR EVALUATING SEISMIC STABILITY OF FOUNDATION ROCK

Figure 13 presents the proposed procedure to be followed during seismic-stability evaluations of the foundation rock. The slip-safety-factor evaluation method based on the equivalent linear analysis yields results that are similar to those obtained using the conventional evaluation method. When the slip safety factor does not satisfy the reference value, the evaluation process (Figure 13) switches over to nonlinear analysis in the next step. During the nonlinear analysis, the progressive failure of rock masses is given due consideration, and the displacements of critical facilities during earthquakes are calculated. Finally, the amount of displacements obtained through nonlinear analyses is compared with the reference values of the allowable inclination, allowable displacements between facilities, etc.

6 CONCLUSION

The centrifugal model test performed in this study confirms the feasibility of the slip-safety-factor evaluation method. In addition, it is observed that the displacement of rock masses because of sliding is limited even when the value of the slip safety factor is less than one. This confirms that in the event of an earthquake, foundation rocks do not become unstable spontaneously. Therefore, the proposed displacement-based method is fully applicable to the seismic-stability evaluations of foundation rocks.

In the future, the authors intend to investigate the reproducibility of the displacement results obtained from centrifugal model tests based on the nonlinear analysis method while considering progressive failure.

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