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The effect of characteristics of back-filling material on the seismic response and stability of castle retaining-walls

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ABSTRACT: Recent earthquakes caused severe damage to the retaining walls of various castles in Japan. In this study, the authors describe this instrumentation, some numerical analyses and the results obtained so far. The site investigations clearly showed that river gravels were used as backfilling materials at the collapsed castle retaining walls. In this study, the authors have investigated the effect of the type of backfilling material on the seismic response and stability of the model castle retaining walls using a shaking table in the laboratory. In addition, a dynamic limiting equilibrium approach was used to investigate the responses and stability of the test results on the model castle retaining walls. The experiments and theoretical studies clearly showed that the type of backfilling material has a great effect on the dynamic response and seismic stability of the walls and the results clearly showed that the castle walls utilizing rounded river gravels as backfilling material are quite vulnerable to fail during great earthquakes. The authors would present the outcomes of the this unique experimental and analytical study and discuss their implications in practice.

1 INTRODUCTION

The 2016 Kumamoto earthquake caused huge damage to Kumamoto Castle. Particularly the retaining-walls of the Kumamoto castle was heavily damaged (Aydan et al. 2018). Similar events were also observed on the retaining walls of Sunpu Castle in Shizuoka due to the 2009 Suruga Bay earthquake, Katsuren Castle due to the 2011 Off-Okinawa earthquake, Shirakawa Castle due to 2011 Great East Japan earthquake. The site investigations at the damaged sites clearly indicated that river gravels were used as backfilling materials at the collapsed castle retaining walls (Fig. 1).

The effect of the type of backfilling material on the seismic response and stability of the model castle retaining walls were investigated using a shaking table in the laboratory in the University of the Ryukyus. Three different back-filling materials were used. Furthermore, laboratory shear tests on the backfilling material and friction coefficient between the backfilling material and the retaining wall material were performed. In addition, a dynamic limiting equilibrium approach was used to investigate the responses and stability of the test results on the model castle retaining walls. The shaking table experiments clearly showed that the type of backfilling material has a great effect on the dynamic response and seismic stability of the walls and the results clearly showed that the castle walls utilizing rounded river gravels as backfilling material are quite vulnerable to fail during great earthquakes. The dynamic limiting equilibrium method was able to confirm the experimental results theoretically. The outcomes of the this unique experimental and analytical study are presented and discussed with an emphasis on their implications in practice.

2 SHAKING TABLE AND MODELS

2.1 *Shaking table and instrumentation*

The shaking table used for model tests was produced by AKASHI. Its operation system was recently updated by IMV together with the possibility of applying actual acceleration wave forms from earthquakes. Table 1 gives the specifications of the shaking table and monitoring devices. The size of the shaking table is 1000 x 1000 mm^2. The maximum acceleration is 600 gals for a model with a weight of 100 kgf. The displacement

Figure 1. Some examples of castle-wall damage in recent earthquakes.

Table 1. The specifications of monitoring sensors and shaking table.

Shaking table and sensors	Specifications	
Shaking Table - AKASHI	Frequency Stroke Acceleration	1-50 Hz 100 mm 600 gals
Accelerometers	Range	10G
Laser Displacement Transducer OMRONKEYENCE	Range Range	0-300 mm 0-100 mm

response of models were monitored using laser displacement transducers and the input acceleration of the shaking table and acceleration response of the retaining wall were measured using the two accelerometers.

2.2 *Model setup*

An acrylic transparent box with 630 mm in length, 300 mm in height and 100 mm width was used as shown in Fig. 2. The wall-thickness was 10 mm so that the box was relative rigid and the frictional resistance of sidewalls was quite low.

The blocks used were made of Ryukyu limestone with a size of 40x40x99.5 mm with the consideration of materials used for the retaining walls of historical castles in Ryukyu Archipelago. Furthermore, the base block was such that the overall wall inclination can be chosen as 70, 83 and 90 degrees. The base block was fixed to two-sided tapes to the base of the acrylic box. In addition, the Ryukyu limestone of the same size was laid over the base as seen in Fig. 2. This was expected to provide a condition similar to the actual conditions observed in many historical castles in Ryukyu Archipelago. The wall height was 240 mm and the ratio of the height to width was 1/6. When the retaining wall inclination is 90 degrees without backfill material, it is expected that the wall would start rocking at an acceleration level of 167 gals.

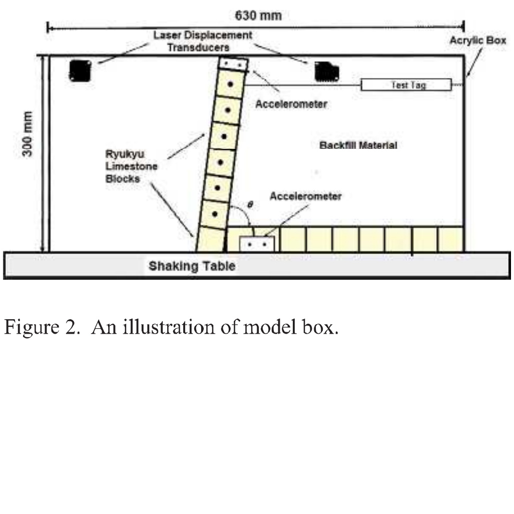


Figure 2. An illustration of model box.

3 BACKFILL MATERIALS AND THEIR PROPERTIES

3.1 *Backfill materials*

Three different backfill materials were chosen (Fig. 3). Glass beads were chosen to represent the lowest shear resistant backfill material while the angular fragments of Motobu limestone was selected as the highest shear resistant backfill material. The third backfill material was rounded river gravels having a shear resistant in-between those of the two previous backfill materials.

3.2 *Properties of backfill materials*

A special shear testing set-up was developed to obtain the shear strength characteristics of backfill materials under low normal stress levels, which are quite relevant to the model tests to be presented in this study. Fig. 4 shows the shear testing device. Fig. 5 shows the shear strength envelopes for three backfill materials. As noted from the figure, shear strength of rounded river gravel is in-between the shear strength envelopes of glass-beads and Motobu limestone gravel. The strength of backfill materials

Figure 3. Views of backfill materials.

Figure 4. A view of shear testing device under low normal stress level.

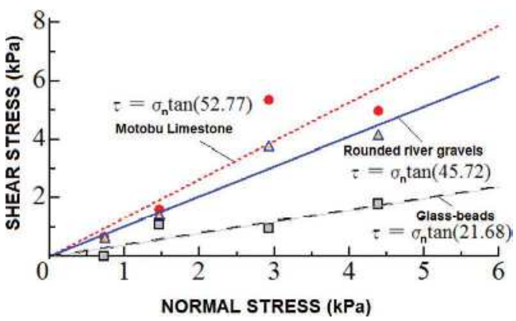


Figure 5. Shear strength envelopes for backfill materials.

is frictional and the friction angle of the glass-beads is about 21.68 degrees.

Another important factor for the stability of the retaining walls of historical castles as well as other similar structures is the frictional resistance between the backfill material and retaining-wall blocks. For this purpose, tilting experiments were carried out. The backfill material contained in a box put upon the Ryukyu limestone platens without any contact and tilted until it slides. This response of the backfill material contained in box was measured using laser-displacement transducers. The inferred friction angles are given in Table 2. The lowest friction angle was obtained in case of glass beads as expected.

4 SHAKING TABLE TESTS ON RETAINING-WALLS WITH GLASS-BEADS BACKFILL

A series of sweep tests were carried before the failure tests. Regarding the glass-beads backfill material, the retaining walls were statically unstable for 90 degrees while they failed during the sweep test on the retaining walls with an inclination of 83 degrees. Therefore, we could show one example for retaining walls for the inclination of 70 degrees (Fig. 6). Its Fourier spectra analysis is shown in Fig. 7. The results indicated no apparent natural frequency was dominant. The situation was quite similar in all experiments. Therefore, more emphasis will be given to the failure experiments.

Although the test on the retaining wall with an inclination of 83 degrees was intended for a sweep test, it resulted in failure. Fig. 8 shows the displacement and base acceleration during the test.

Table 2. Friction angle between Ryukyu limestone and backfill materials.

Parameter	Glass-beads	Rounded river gravel	Motobu limestone fragments
Friction angle	12.5-16.8	25.0-27.5	25.9-27.8

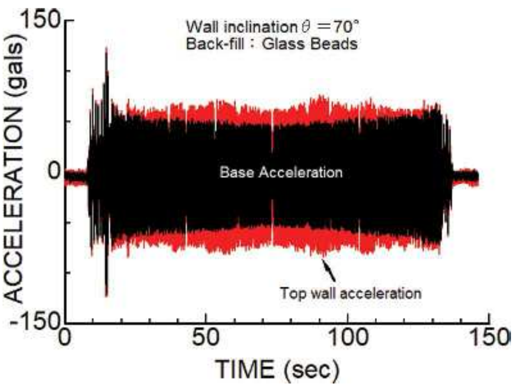


Figure 6. Acceleration records of the shaking table and top of the retaining wall.

Failure tests on the retaining walls with an inclination of 70 degrees were carried out by applying sinusoidal waves with a frequency of 3Hz. The amplitude waves were gradually increased until the failure occurred. Fig. 9 shows an example of failure. The yielding initiated at about 110 gals and the total failure occurred when the input acceleration reached 215 gals. Fig. 10 shows the retaining wall

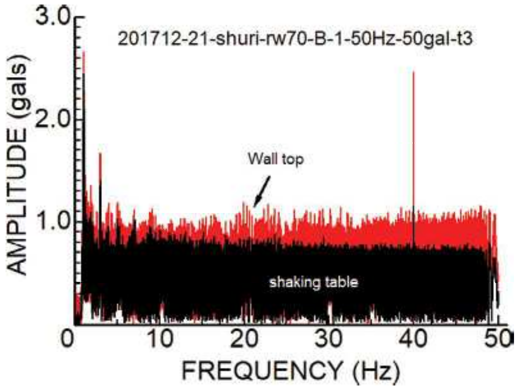


Figure 7. Fourier spectra of acceleration records.

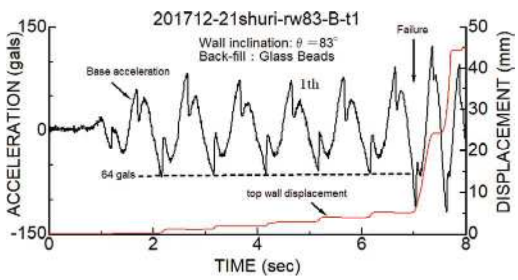


Figure 8. Acceleration and displacement responses on the retaining wall with an inclination of 83 degrees.

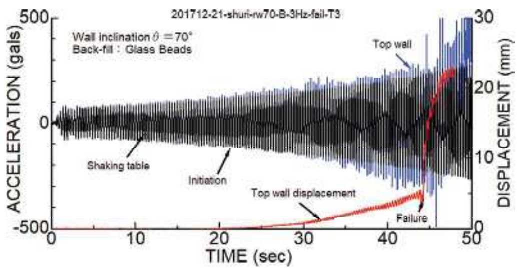
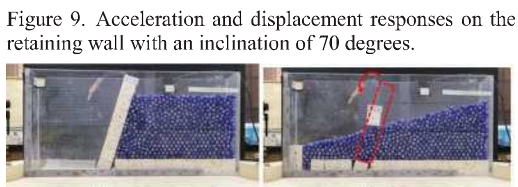


Figure 9. Acceleration and displacement responses on the retaining wall with an inclination of 70 degrees.



(a) Before (b) After

Figure 10. Views of the model retaining wall with an inclination of 70 degrees before and after the test.

before and after the failure test. The retaining wall failed due to toppling (rotation) failure although some relative sliding occurred with the block at the toe of the model retaining wall.

5 SHAKING TABLE TESTS ON RETAINING-WALLS WITH RIVER GRAVEL BACKFILL

A series of sweep tests were carried before the failure tests as explained in the previous section. Regarding the rounded river gravel backfill material, the retaining walls were statically unstable for 90 degrees while the sweep test on the retaining walls with an inclination of 83 and 70 degrees could be carried. We show one example for retaining walls for the inclination of 83 degrees in Fig. 11 and its Fourier spectra analysis in Fig. 12. The results indicated there was no dominant natural frequency for the given range of frequency. The situation was quite similar in all experiments for 83 and 70 degrees retaining wall models.

Failure tests on the retaining walls with inclinations of 83 and 70 degrees were carried out by applying sinusoidal waves with a frequency of 3Hz. The amplitude waves were gradually increased until the failure occurred. Figs. 13 and 14 show acceleration and displacement responses of retaining walls with inclinations of 83 and 70 degrees as examples of failure tests. The yielding initiated at about 100 gals and the total failure occurred when the input acceleration reached 210 gals for 83 degrees retaining walls. On the other hand, the yielding initiated at 220 gals and the total failure occurred when the input acceleration was 430 gals for 70 degrees retaining walls as seen in Fig. 15. The retaining wall failed due to toppling (rotation) failure although some relative sliding occurred with the block at the toe of the model retaining wall (Fig. 15).

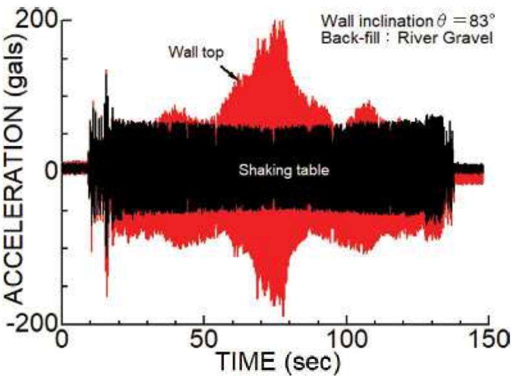


Figure 11. Acceleration records of the shaking table and top of the 83 retaining wall with rounded river gravel backfill.

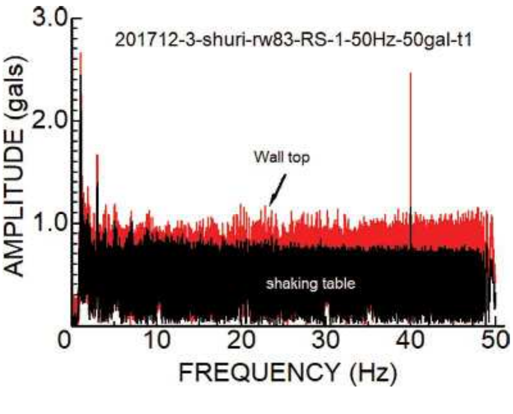


Figure 12. Fourier spectra of acceleration records.

6 SHAKING TABLE TESTS ON RETAINING-WALLS WITH MOTOBU LIMESTONE GRAVEL BACKFILL

A series of sweep tests were carried before the failure tests as explained in the previous section. Regarding the angular Motobu limestone gravel backfill material, the retaining walls were statically unstable for 90 degrees with a height of 240 mm. However, they were stable when the height was reduced to 160 mm. The sweep test on the retaining walls with an inclination of 90, 83 and 70 degrees wee carried. We show

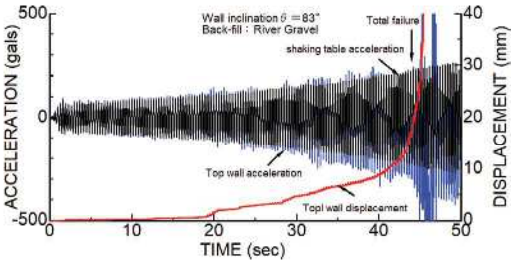


Figure 13. Acceleration and displacement responses on the retaining wall with an inclination of 83 degrees.

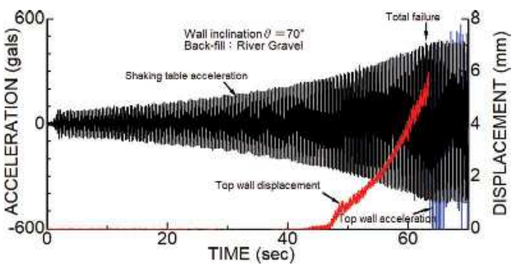


Figure 14. Acceleration and displacement responses on the retaining wall with an inclination of 70 degrees.

(a) Before (b) After

Figure 15. Views of the model retaining wall with an inclination of 70 degrees before and after the test.

one example for retaining walls for the inclination of 70 degrees in Fig. 16 and its Fourier spectra analysis in Fig. 17. Again, the results indicated there was no dominant natural frequency for the given range of frequency. The situation was quite similar in all experiments for 90, 83 and 70 degrees retaining wall models.

Failure tests on the retaining walls with inclinations of 90, 83 and 70 degrees were carried out by applying sinusoidal waves with a frequency of 3Hz. The procedure was the same those in previous experiments. Figs. 18, 19 and 20 show acceleration and displacement responses of retaining walls with

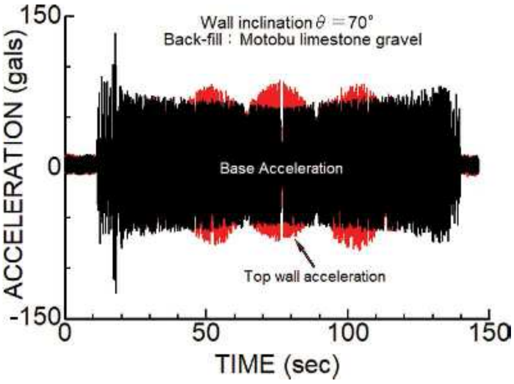


Figure 16. Acceleration records of the shaking table and top of the 70 degrees retaining wall with rounded river gravel backfill.

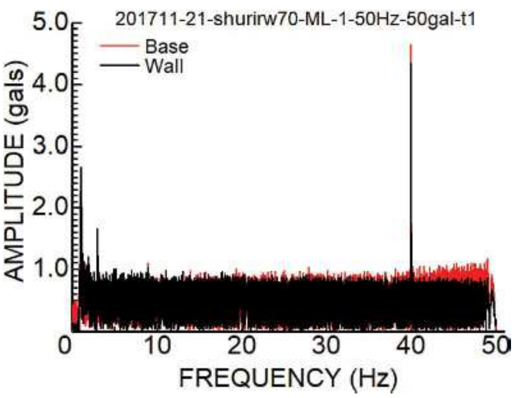


Figure 17. Fourier spectra of acceleration records.

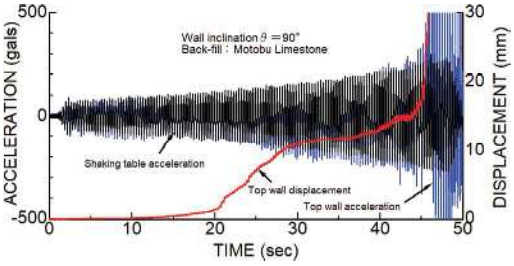


Figure 18. Acceleration and displacement responses on the retaining wall with an inclination of 90 degrees.

inclinations of 90, 83 and 70 degrees as examples of failure tests. The yielding initiated at about 110 gals and the total failure occurred when the input acceleration reached 260 gals for 90 degrees retaining walls. On the other hand, the yielding initiated at 130 gals and the total failure occurred when the input acceleration was 300 gals for 83 degrees retaining walls as seen in Fig. 19. The retaining walls failed due to toppling (rotation) failure.

The retaining walls with 70 degrees inclination and height of 240 mm did not failed during the entire test up to 400 gals as seen in Figs. 20 and 23. Although some relative sliding occurred with the block at the toe of the model retaining wall when the base acceleration reached to the level of 300 gals (Fig. 23). However, some settlement of the backfill occurred and the retaining wall was pushed in passive sliding mode.

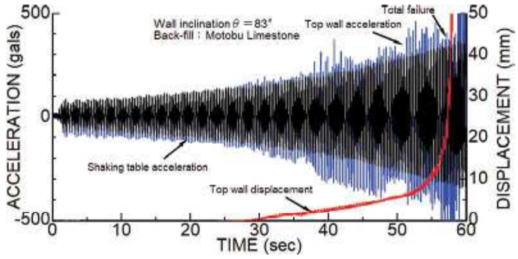


Figure 19. Acceleration and displacement responses on the retaining wall with an inclination of 83 degrees.

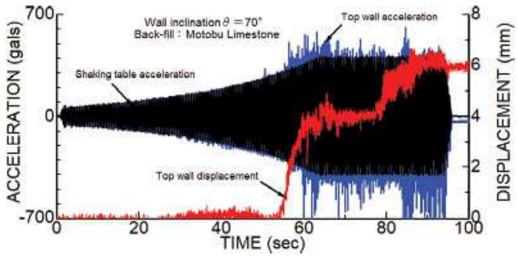


Figure 20. Acceleration and displacement responses on the retaining wall with an inclination of 70 degrees.

(a) Before (b) After

Figure 21. Views of the model retaining wall with an inclination of 90 degrees before and after the test.

(a) Before (b) After

Figure 22. Views of the model retaining wall with an inclination of 83 degrees before and after the test.

(a) Before (b) After

Figure 23. Views of the model retaining wall with an inclination of 70 degrees before and after the test.

7 DYNAMIC RESPONSE ANALYSES

Aydan (2017), Aydan et al. (2003) and Tokashiki and Aydan (2007) proposed a dynamic equilibirum method to analyse the acceleration and displacement response as well as the stability of retaining walls. The retaining walls generally fail in three modes; sliding failure, toppling failure and combined sliding and toppling failure as illustrated in Fig. 24. This method applied to the experiments shown in previous sections. Figs. 25 to 27 shows the comparison of computed results with experimental results for selected retaining walls with the consideration of toppling and sliding modes with and without sidewall resistances. Material properties used are also shown in the figures. Although the computed results estimate the failure of retaining walls at lower acceleration levels, it is capable of estimating the dynamic displacement responses during failure.

8 CONCLUSIONS

The recent earthquakes such as the 2016 Kumamoto earthquake damaged the Castles, especially, their retaining-walls. Site investigations showed that rounded river gravels were generally used as backfill materials at collapsed castle walls. The effect of three backfilling materials on the seismic stability of the model castle walls was investigated through shaking table model tests. Furthermore, the frictional strength between the backfill material and castle walls is measured. The shaking table experiments showed that the type of backfilling material has a great effect on the seismic stability of the walls and the castle walls utilizing rounded river gravels are quite vulnerable to fail during great earthquakes. Furthermore, the dynamic limiting equilibirum method used for simulating the shaking table tests and it was found that it was possible to evaluate the displacament responses of the retaining walls.

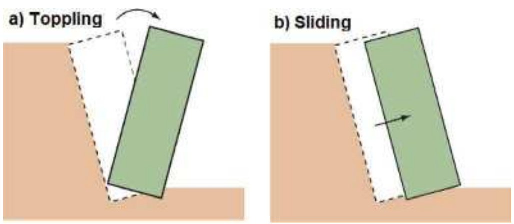


Figure 24. Failure modes of retaining walls.

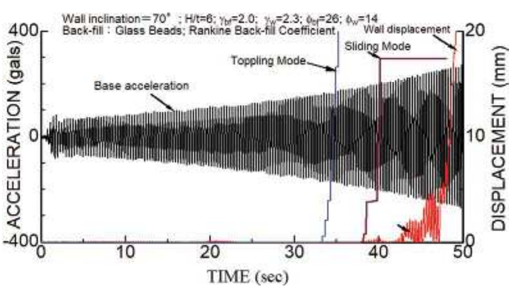


Figure 25. Comparison of computations with experimental data for the 70 degrees retaining wall with glass-beads backfill.

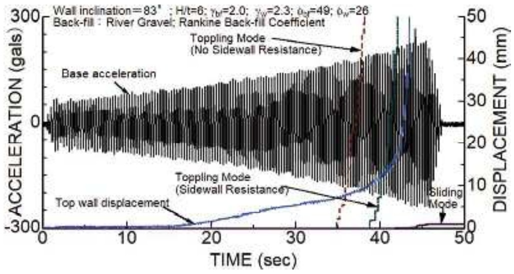


Figure 26. Comparison of computations with experimental data for the 83 degrees retaining wall with river gravel backfill.

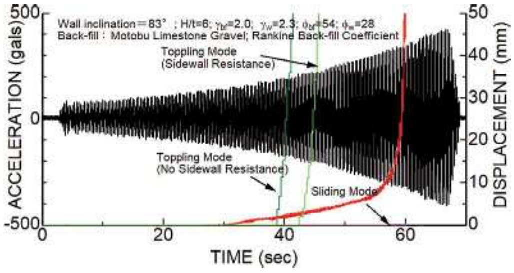


Figure 27. Comparison of computations with experimental data for the 83 degrees retaining wall with limestone gravel backfill.

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