Included in Proceedings of 2019 Rock Dynamics Summit in Okinawa
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2019 Rock Dynamics Summit– Aydan et al. (eds)
© 2019 Taylor & Francis Group, London, ISBN 978-0-367-34783-3

An experimental study on the formation mechanism of tsunami boulders

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ABSTRACT: There are many tsunami boulders in the islands of the Ryukyu Archipelago. Among them, tsunami boulders in Okinawa (Kasakanja), Miyako (Higashi-Hennasaki), Shimojiri (Obiwa) and Ishigaki (Ohama) Islands are famous. These tsunami boulders are definitely due to the past mega-tsunamis. An experimental study has been undertaken on the mechanism of tsunami boulders by using a specially developed tsunami generation device. Various single blocks having different densities and cliff models with different geometry and materials are prepared and tested. The experiments shown that tsunami boulders found on terraces are likely to be associated with cliffs having a toe erosion and failing like passive flexural toppling failure. The authors describe these experimental studies and discuss their implications in the tsunami boulder formation as well as the estimation of mega-earthquakes.

1 INTRODUCTION

Tsunami induced boulders are found worldwide and the mechanism involved in the formation of such tsunami boulders is still controversial. There is no doubt that such huge tsunami boulders can only be caused by huge tsunamis resulting from mega-earthquakes. There are many tsunami boulders in the islands of the Ryukyu Archipelago. Among them, tsunami boulders in Okinawa (Kasakanja), Miyako (Higashi-Hennasaki), Shimojiri (Obiwa) and Ishigaki (Ohama) Islands are famous and they are definitely due to the past mega-tsunamis (Aydan and Tokashiki, 2018). The authors have initiated an investigation program to quantify the geometry and position of tsunami boulders and topographical conditions in their close vicinity including the erosion state along the shoreline. However, the formation of tsunami boulders and associated conditions are quite important for both understanding the past mega-earthquakes and future earthquakes in relation to the preparation of disaster mitigation plans.

The authors have developed an experimental device to investigate the formation mechanism of tsunami boulders. The device is capable of inducing both tsunami waves due to thrust faulting and normal faulting. The model cliffs with toe erosion were prepared. The cliffs were either continuum type or blocky type. The continuum type cliffs were prepared using plaster while the blocky cliffs were made of Ryukyu limestone blocks. The experiments were carried under different velocities of faulting and the geometry of the model cliffs. The experiments shown that tsunami boulders found on terraces are likely to be associated with cliffs having a toe erosion and failing like passive flexural toppling failure. The authors will describe the findings from these experimental studies and discuss their implications in the tsunami boulder formation as well as the estimation of mega-earthquakes.

2 OBSERVATIONS ON TSUNAMI BOULDERS IN RYUKYU ARCHIPELAGO

The present observations were made on selected tsunami boulders in Okinawa (Kasakanja), Miyako (Higashi-Hennasaki), Shimojiri (Obiwa) and Ishigaki (Ohama) Islands (Fig. 1), which are definitely due to the past mega-tsunamis. For this purpose, the authors have been utilizing aerial photogrammetry and laser scanning techniques to map the boulders and their geometrical locations with respect to the topography. Although the tsunami boulders in Ishigaki, Miyako and Shimoji islands were initially believed to be due to the 1771 Meiwa earthquake with an estimated magnitude of 7.4 (Aydan and Tokashiki 2007), the recent studies indicated by Aydan and Tokashiki (2018) that they were much older. Particularly, the tsunami boulder in Shimoji Island is probably the largest in the world. Table 1 gives the size and elevation of the tsunami boulders and their distance to the nearby cliffs in selected locations. In addition, some large boulders of metamorphic origin and sandy tsunami deposits were observed by the authors within Ryukyu limestone layer during an excavation of a large engineering structure in Ishigaki Island (Aydan and Tokashiki 2018). These observations also imply that the events were cyclically occurring in Ryukyu Archipelago.

One can also find many boulders on the tsunami-induced boulders., which we call "Sea Tsunami Boulders" (Fig. 2). However, it is extremely difficult to differentiate from the boulders resulting from cliff

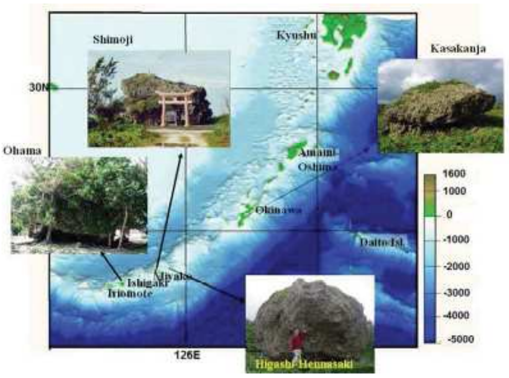

Figure 1. Major islands of the Ryukyu Archipelago and selected huge tsunami boulders in (base map from 11th Regional Coast Guard Headquaters of Japan).

failures into the sea due to toe erosion resulting from the ordinary action of sea waves (Tokashiki and Aydan, 2010). The rockblocks failed due to toe-erosion may look-like tsunami boulders distributed around Ryukyu Islands resulting in mis-interpretations (Fig. 3).

3 MODEL TSUNAMI GENERATION DEVICES

The authors performed two series of experiments using model tsunami generation devices. The first series of experiments were done at Tokai University and the second series of experiments were done in the University of the Ryukyus. Brief summary of these experiments are outlines in this section.

3.1 *Experimental facility at Tokai University*

The tsunami generation model is made of 2000 mm long, 300 mm wide and 400 mm high acrylic box. Fig. 4 shows illustrates the concept of rising sea wave and receding wave type tsunami modeling. The inclination of the sea bottom was 1/10. The water level change was about 100 mm. Single rectangular prism type blocks made of Ryukyu limestone or porous concrete were tested. Several overhanging configurations were also tested. Furthermore, the performance of boulder type wave-breaks were also tested.

Table 1. Elevation and height of tsunami boulders from selected locations

Location	El.(m)	H(m)	L(m)	W(m)	DtoC(m)
Hennazaki	20	4	6.8	4.5	21
Obiwa	12.5	9.0	16	14	43
Kasakanja	12	3	7.5	5	34
Ohama	8.0	5.9	12	11	96

El.: Elevation; H:Height; L:Length; W: Width; DtoC:Distance to cliff

Figure 2. Sea tsunami boulders in Ishigaki Island.

Figure 3. Toe erosion and subsequent cliff failures.

3.2 *Experimental facility at the University of Ryukyus*

Following the preliminary attempts at Tokai University, the third author designed a tsunami generation device OA-TGD2000X to study the tsunami waves due to thrust and normal faulting event shown in Fig. 5. The dimensions and characteristics of the

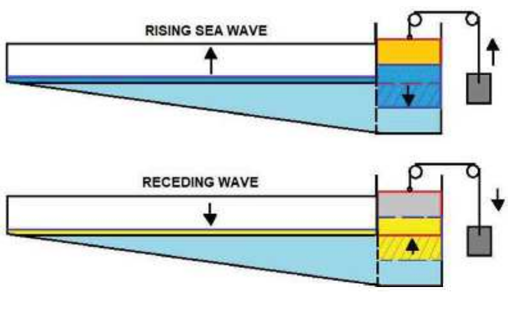

Figure 4. Illustration of the basic concept of tsunami generation device at Tokai University.

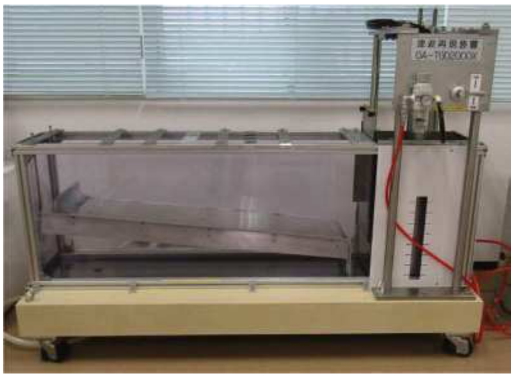

Figure 5. A view of the tsunami generation device OA-TGD2000X.

device was quite similar to that used in Tokai university except the wave-induction system. A tank was lowered or raised through pistons with a given velocity to generate rising or receding tsunami waves. The pressure and wave velocity at specified locations were measured using pressure sensors and the amount of tank movement was measured using laser transducers. Fig. 6 shows an example of record during the movement of tanks inducing rising and receding tsunami waves.

4 EXPERIMENTS AT TOKAI UNIVERSITY

4.1 *Ryukyu limestone blocks*

First Ryukyu limestone blocks with a height of 100 mm and width of 40 mm immersed to a depth of 30mm initially were subjected to different tsunami wave with different wave height. When the final water level variation was less than 40 mm, the blocks slid upward as seen in Fig. 7. However, if the final water level variation was more than 60 mm, the blocks were toppled landward in the direction of tsunami wave propagation as seen in Fig. 8. Fig. 9 shows the experiments at several time intervals. The movements of the blocks occurred mainly during the water level rise stage and there was almost no movement during the receding wave stage.

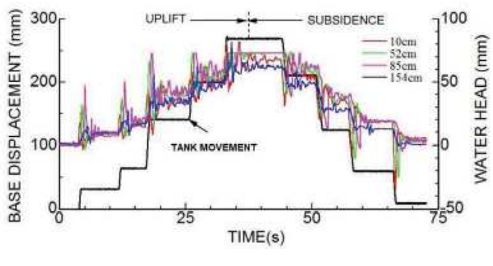

Figure 6. Water head response at specified locations in relation to the tank movement.

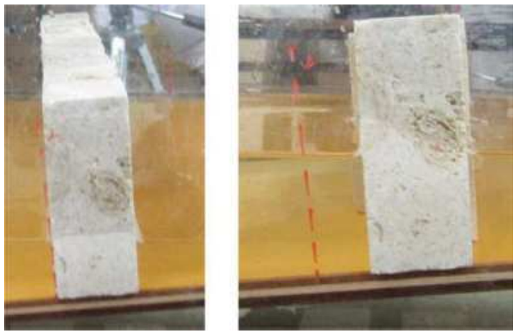

Figure 7. A view of Ryukyu limestone blocks before and after the test.

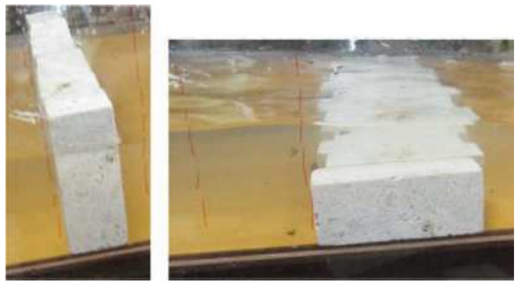

Figure 8. A view of Ryukyu limestone blocks before and after the test.

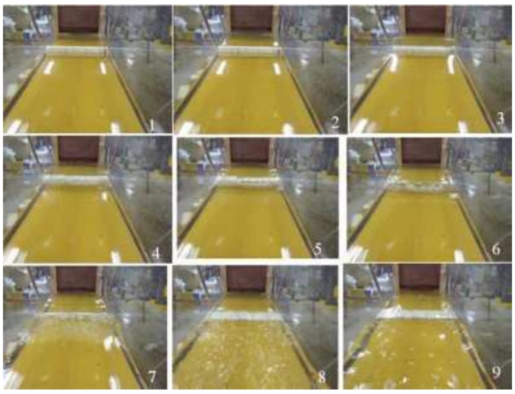

Figure 9. Views of the test shown in Figure 8 at different time steps.

4.2 *Porous concrete blocks*

Next porous concrete blocks having dimensions of 150 mm height and 50 mm width were tested as shown in Figs. 10 and 11. As the density of the blocks is lower than that of Ryukyu limestone and the height over width ratio is higher, they easily toppled as seen in the Figures.

4.3 *Experiments on boulder type wave-breaks*

The final experiment was carried out on the performance of boulder-type wave-breaks. The stone was

Figure 10. A view of porous concrete blocks before and after the test.

siliceous sandstone from Abe River in Shizuoka Prefecture belonging the Shimanto River Formation. The height of the wave-break was 50 mm and it was immersed in water up to 25 mm. The final water level rise was about 25 mm after the test. Fig. 12 shows side and top views of the wave-break before and after the experiment. As seen from the figure, the wave-break subsides and spreads due to the tsunami waves. In other words, the boulders are displaced by the generated tsunami waves. Fig. 13 shows the experiment at time intervals. As noted from the figure the boulders are displaced during the overflow process of the tsunami waves. The receding tsunami waves do not cause major movements during the experiment.

5 EXPERIMENTS AT THE UNIVERSITY RYUKYUS

5.1 *Triangular Ryukyu limestone blocks*

Rectangular prism blocks were tested and the results were quite similar to those tested in Tokai University. A triangular shaped prismatic blocks shown in Figs. 14 and 15 tested under the same condition. The longest side of the triangular prismatic

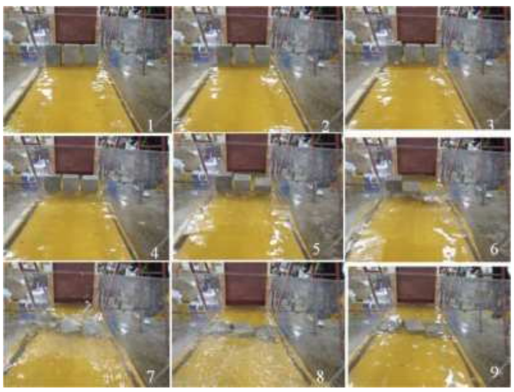

Figure 11. Views of the test shown in Figure 10 at different time steps.

Figure 12. Side and top views of experiment on wave-breaks

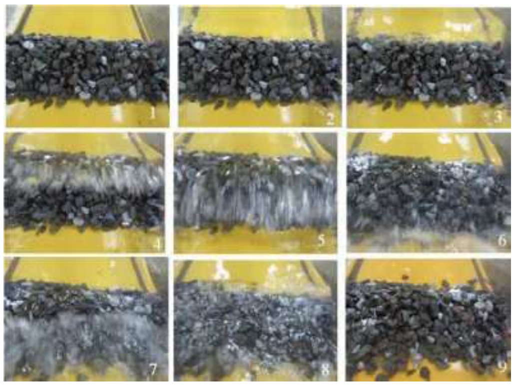

Figure 13. Views of the test shown in Figure 12 at different time steps.

block shown in Fig. 14 was downward while the longest side of the triangular prismatic block shown in Fig. 15 was upward. While the downward triangular prismatic block was almost non-displaced, the upward triangular prismatic block was considerably displaced. One of the main reasons for such big difference when they are subjected to the tsunami forces is that the tsunami wave apply a surging uplift force on the block. As for the downward triangular prism the surging force increases the normal force on the block. We also put a rectangular prism Ryukyu limestone next to the triangular prismatic block. The displacement of the rectangular block was quite small.

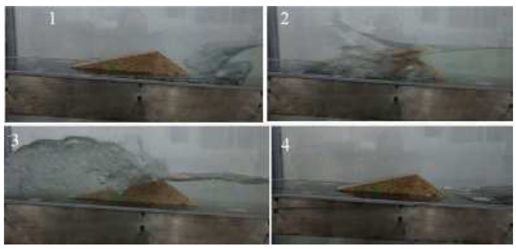

Figure 14. Views of the downward triangular prism block at different time steps

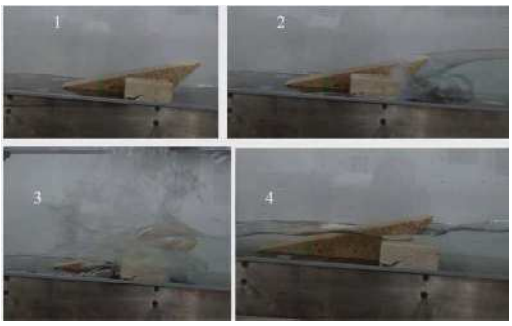

Figure 15. Views of the upward triangular prism block at different time steps

5.2 *Plaster blocks*

First a rectangular prismatic block made of plaster was subjected to rising tsunami waves as shown in Fig. 16. The overall behaviour is fundamentally similar to those tested in Tokai University. Nevertheless, the block was toppled towards downstream side and displaced horizontally in the direction of receding tsunami waves as seen in Fig. 16.

Next two plaster prismatic blocks laid over the Ryukyu limestone blocks as shown in Fig. 17. The density of the plaster blocks is almost half of that of the Ryukyu limestone blocks. As seen from images 2 and 3 in Fig. 17, the plaster blocks thrown upward and displaced in the direction of the tsunami waves. This experiment clearly demonstrates the importance of the density and overhanging degree of blocks when they are subjected to tsunami waves in nature.

5.3 *Breakable overhanging cliffs*

The next series of experiments involve the breakable blocks. Finding appropriate material for breakable blocks under the forces induced by tsunami forces by the experimental device was quite cumbersome. Although the materials had a very small density as compared those in nature, it provided an insight view on the mechanism of formation of tsunami boulders, which was the main goal of this study. Figs. 18 and 19 show the images of the models during at different time steps. The surging tsunami wave enters under the overhanging blocks and applies upward forces. As a result, the overhanging block starts to bend upward and they are broken after a certain amount of the displacement. In other words, the failure of the overhanging blocks are quite close to cantilever beams. However, the failure of the overhanging blocks is against the gravity. Once the block is broken, it is dragged by overflowing tsunami waves. This observation is in accordance with the mechanism proposed by Aydan and Tokashiki (2019) for the formation of tsunami boulders. Our experiments clearly indicated that if the inclination of the lower side of the overhanging block ranges between 10-20 degrees, they are quite vulnerable to fail.

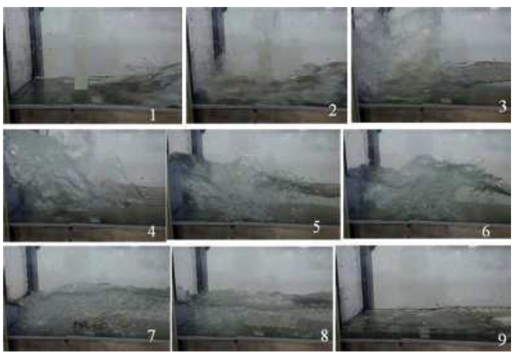

Figure 16. Views of the plaster block test at different time steps.

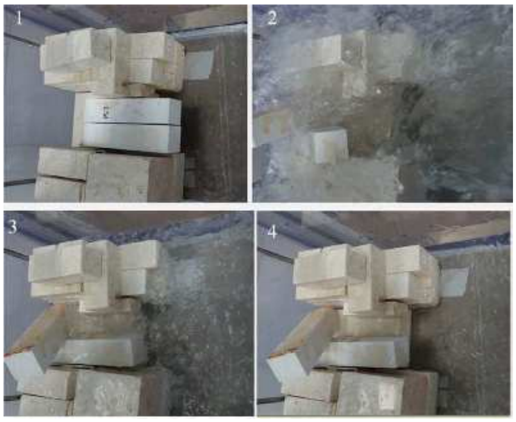

Figure 17. Top views of the plaster block overhanging over the base Ryukyu limestone blocks at different time steps.

6 SOME CONSIDERATIONS ON THE FORMATION OF TSUNAMI BOULDERS AND THEIR MOVEMENTS

6.1 *Mechanism of formation of tsunami boulders*

Figures 18 and 19 show how tsunami waves breaks at the model overhanging rock cliffs. When the wave hits the cliff or rock block it is reflected and a huge splash

Figure 18. Views of the experiments using a breakable overhanging block at different time steps.

Figure 19. Views of the experiments using a breakable overhanging block at different time steps.

occurs in proportion to sea-wave pressure. As the cliffs of Ryukyu limestone is quite prone to dissolution by sea water and erosion by sea waves, they result in overhanging cliffs. As studied by Tokashiki and Aydan (2010) and Horiuchi et al. (2018), the overhanging cliffs are quite prone to failure by bending under gravitational and seismic forces. However, storm-waves and tsunami waves may also cause the failure of overhanging cliffs. As noted in Figures 18 and 19, the impact force by the storm-waves or tsunamis may particularly cause the bending failure of overhanging cliffs against gravity and throw the broken overhanging blocks onto the cliff terraces. If rock mass is blocky due to the existing discontinuities, they may displace the blocks resulting in active or passive toppling or other failure modes (e.g. Aydan and Tokashiki 2018; Aydan et al. 1989). However, if the rock mass is continuum type, the failure due to huge impact forces induced by tsunamis may result in a failure mode similar to the passive type flexural toppling failure (Aydan and Kawamoto, 1992) as observed previously by Aydan and Amini (2006) as well as by Horiuchi et al. (2018) in shaking table tests on rock slopes. Aydan and Amini (2006) also developed some analytical solutions for the passive flexural failure of cantilever beams under seismic forces. In view of these experiments, observations and analytical studies, the impact force, which is a function of characteristics of tsunami, is a decisive factor to throw the tsunami boulders onto cliff terraces.

6.2 *Movement of tsunami boulders*

Once the broken overhanging blocks thrown over the terraces, they will be subjected to water pressure, uplift and drag forces. As a result, the broken boulder or boulders may be moved by translation, toppling or both as observed in Fig. 1. If the boulders existing near shorelines may be moved the landward by rising tsunami waves or away from the shoreline by receding tsunami waves as seen in Fig. 2. The amount of the movements would undoubtedly depend upon the resulting tsunami waves as a function of magnitude of the earthquake or displaced water body in case of slope failure, meteorite impact or volcanic eruption.

7 CONCLUSIONS

The authors reported some experimental studies at the University of the Ryukyus and Tokai University over a period of two years. Various blocks having different densities and cliff models with different geometry and materials are prepared and tested using the tsunami generation devices at both institutes. Some overhanging cliffs consisting of breakable overhanging parts prepared and tested. From this experimental study, the following conclusions may be drawn:

(1) Blocks of different shape and densities can be translated, toppled or both. Most of the movements results from the rising tsunami waves and run-up stage. Nevertheless, some blocks may also be displaced during receding tsunami wave stage. However, if the shape of the boulders such that the blocks may not move at all.

(2) When the surging tsunami wave enters under the overhanging blocks and applies upward impact forces. As a result, the overhanging block bends upward and they may be broken after a certain amount of the displacement. Once the block is broken, it is dragged by overflowing tsunami waves.

(3) Experiments indicated that if the inclination of the lower side of the overhanging block ranges between 10-20 degrees, they are quite vulnerable to fail.

(4) Experiment on the performance of boulder-type wave-breaks indicated that the wave-break subsides and spreads due to the tsunami waves. The boulders are displaced during the overflow process of the tsunami waves. The receding tsunami waves do not cause major movements during the experiment.

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