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MECHANISM OF SEAWALL DESTRUCTION DUE TO TSUNAMI

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ABSTRACT

Tsunami that happened along Sunda Strait on 22 December 2018 was generated by the collapse of the flank of Anak Krakatau volcano in Indonesia. The tsunami hit Lampung and Sunda beaches areas. The hydrodynamic force of the tsunami hit everything on its course severely including seawalls that are used to protect the beach from erosion due to wind waves. The stability of such structure is limited to the design wind wave force. Tsunami has a significantly different nature compare to wind waves. When tsunami arrives at the coastline it becomes surge where, the water particle movement is significantly faster than that of the wind waves. The force of such high speed of water particles at a seawall may destroy and drag away the material far from the original location. Field survey was conducted following the tsunami event along Sunda Strait in Banten area. Based on the survey, a hydraulic simulation of seawall destruction due to tsunami was carried out in the laboratory. It was found that there were two distinct mechanisms of seawall destruction. When the land support of the seawall is relatively weak, the seawall may be dragged landward. However, when the land support behind the seawall is relatively strong, for example more than 40% of the seawall's total height that stabilize the seawall against the turning moment, the seawall may be dragged seaward by the tsunami return flow (run down). These mechanisms are relevant to tsunami mitigation. Consideration of seawall collapse due to return flow of tsunami should be taken into account since, normally tsunami is a wave train that attacks the beach in a series.

Keywords: *Tsunami, Seawall, Ruins, Mechanism, Physical Model*

1. INTRODUCTION

On 22 December 2018, a tsunami stroked Sunda Strait both along the Banten and Lampung coastal areas of Indonesia. The tsunami was induced by the collapse of the flank of Anak Krakatau Volcano (BMKG, 2018). It was a unique tsunami generation since no significant tremor was recorded prior to the tsunami event. Anak Krakatau erupted on 21 December 2018 and was followed by the second eruption on 22 December 2018 (BMKG, 2018). The volcano eruption was followed by a collapse of the flank into the sea which triggered the tsunami (BMKG, 2018). The location of Anak Krakatau Volcano is presented in Figure 1. A numerical simulation was conducted by (Giachetti et al., 2012). They reported that the slides caused an initial tsunami of 43 m.

The tsunami caused various damages along the coastal areas surrounding the Sunda Strait. Based on post tsunami survey, the heights and damage patterns in Lampung and Banten coastal areas significantly varied (Takabatake et al., 2019). Such variations could have been caused by the bathymetry, position and size of slides, and times of slides occurrence. So far, the surveys that were carried out along the affected areas was focused on tsunami height, inundation and run up. Information and discussion about the effect of the tsunami especially related to seawall and debris has not been reported so far. As occurred in the Aceh tsunami in 2004 and the East Japan tsunami in 2011, many types of debris can be devastating to other buildings and people. In order to mitigate tsunami disaster therefore, the debris and its effect should be minimized. One type of the debris during East Japan tsunami in 2011 is the ruin of seawalls. The destructions were due to the excessive forces of tsunami and scouring behind the seawall (Mikami, et al., 2012; Suppasri et al., 2013; Yeh, et al., 2013; Jayaratne, et al., 2016). Even a strong seawall such as that in Japan could be destroyed. The damaged seawalls have become debris and were drifted away from their original positions. The drifting of debris toward the land is unwanted as it may endanger other buildings or people.

In Indonesia, there is no seawall that was specially built to mitigate tsunami. Normally, seawalls in Indonesia are aimed at protecting the coastal area from erosion. This type of seawall is not designed to withstand the force of tsunami. Hence, it is expected that this type of seawall along the Sunda Strait would be destroyed due to the Sunda Strait tsunami. In order to understand the effect of tsunami on some of the seawall along the coast of Banten (Sunda Strait) a survey was conducted after the tsunami event. The survey was aimed to investigate the damage of structures in the land areas due to the hydrodynamic force of tsunami. Destruction on buildings was also the main concern.

This paper reported a survey on the Sunda tsunami destruction especially regarding the seawalls. Two different conditions of seawall destruction were found during the survey. These were a seawall at Batu Hideung beach and a seawall at Cherry beach. A simple laboratory experiment was carried out to explain the mechanism of seawalls destruction at these two locations.

Figure 1. Sunda Strait and Anak Krakatau Mountain (map from Google Earth image)

2. SURVEY AND EXPERIMENTAL WORKS

2.1 The Field Survey

The field survey was conducted six days after the tsunami event, starting from 28th of December to 31st December 2018. It was expected that after 5 days of the tsunami event, the survey could be conducted more easily whilst most of the destruction and debris have not been removed from their original positions. The survey was conducted at the location where the damage of structures has not been cleared out and where the destruction was still tractable. The survey locations were Kelapa Jangkung Beach, Sukarame Beach, Chery Beach, and Batu Hideung Beach. These areas are tourist destination beaches which are depicted in Figure 2.

Figure 2. Survey locations in Banten Area (map from Google Earth Image)

2.1.1 The type of debris and the destruction

At Kelapa Jangkung beach, it can be seen that coconut tree debris has caused the building near the coast suffered from destruction. Figure 3 suggests that a rooftop was ruined by the debris. At that location the tsunami inundation was less than the roof height, hence the roof of the first-floor must have been ruined by floating debris. The coconut tree that could still be found in front of the building is the most possibly caused of the destruction. In Figure 4, many debris were found in the building adjacent to the building shown in Figure 3. On the right, a brick wall seems to be in a good condition or stable. The car on the background was seriously damaged. Probably the car has been swept by tsunami as debris and hit the building behind it. As can be seen, the car's body was deformed.

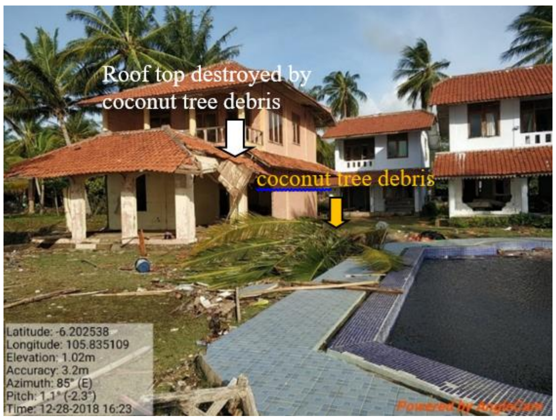


Figure 3. The rooftop of the building was damaged by a coconut tree debris

Figure 4. Debris in front of the building

A steel framework warehouse at Sukarame Beach was hit by tsunami as depicted in Figure 5. The lower part of the enclosure that was made of thin steel sheet was destroyed. The warehouse contained a number of agricultural equipment and machineries such as tractors that were for sales. When tsunami hit the building, all the equipment was washed away as debris and probably has caused further destruction to the enclosure. Some of the equipment was found approximately 150 m from the warehouse. Since there was no building behind the warehouse the debris could have rolled freely into the agricultural area. The debris indicated the strength of the tsunami in this area. Another indicator that demonstrated the strength of tsunami at this location is the fact that a building of brick wall with reinforce concrete frame was completely demolished. The wall with reinforce concrete was much more brittle when compare with the steel building. The ruins have become debris where some of them were drifted landward by tsunami. Approximately 300 m to the south from the warehouse location was a small container hotel location. The hotel was under construction where the containers were prepared near the beach. The containers were swept by tsunami as debris and stopped by trees along the road Figure 6.

Figure 5. The damage warehouse (steel frame, thin sheet steel enclosure) and brick wall with reinforce concrete frame buildings

Some of those containers have been installed on top of a stall foundation approximately 60 cm above the land surface. Figure 7 shows the condition of such container building. The tsunami force swept those containers land ward and luckily many of them were stopped by trees.

Figure 6. Container structure dragged by the tsunami

Figure 7. Survived container building

In the survey area, a seawall was destroyed almost completely as shown by Figure 8. A big boulder can be found on top of the ruined. These boulders could have originally been in front of the seawall (sea side) and were drifted by tsunami and finally hit the seawall. The boulder could have added more destruction to the seawall. In different location a very large boulder (3 m in diameter) was also found in land (Figure 9). The boulder could have been drifted tenth of meters from its original position in the beach. This justify that large boulder can be drifted far away by the Sunda Strait tsunami.

Figure 8. Boulders on top of the seawall in Batu Hideung Beach

Figure 9. Boulder was dragged on land

2.1.2 Seawall destruction

Along the Chery Beach location, a relatively long seawall was constructed, probably to protect the beach from erosion. The seawall was not very strong as it was only made of cemented stones. The seawall was almost completely destroyed by the tsunami. An example of the ruins is given in Figure 10. As can be seen in the figure that, no part of the wall survived (Figure 10(a)). The dotted line represents the approximate original location of the seawall. In fact, some of the ruins were swept and drifted away as debris. This type of debris is also very dangerous for people during the tsunami event where they tried to escape from tsunami. Some of the debris was drifted approximately 50 m away from the beach (Figure 10(b)). Tsunami inundation at this location is about 3 m judging from the marks left by tsunami and dried leave of the coconut tree.

Another seawall in different location which is at Batu Hideung Beach (Figure 11) was also destroyed. This was a relatively new seawall construction. Similarly, the seawall was aimed at protecting the beach area from erosion. The depth of the foundations of both the Chery Beach and Batu Hideung are approximately 0.5 m.

(a) (b)

Figure 10. Seawall damage in Chery Beach Banten

Figure 11. Seawall damaged at Batu Hideung Beach Banten

Unlike the debris of seawall at Chery Beach, the ruins of Batu Hideung seawall were scattered at the seaside. There could have been a number of possibilities. First, the seawall was strong enough to withstand tsunami during run up due to the land support but, it was failed during the rundown time as no land support at the seaside. Second, there was a possibility that the area behind the seawall was inundated due to tsunami coming from adjacent location since the tsunami height along Sunda Strait varied considerably. For example, the inundation at Sukarame Beach were approximately 2 to 3 meters, however at TPI Sukanegara (fish auction) which is only 660 m to the north, there was almost no inundation on land. A witness whose house is near the fish auction explained that he could only saw that, the water of the river mouth (used as fishing boat harbor) was turbulence and that the boats were hitting each other very hardly. He confirmed that there was no significant inundation at that location. The rundown of the tsunami was probably the one that destroyed the seawall. This analysis is also supported by the fact that there is a hill at 120 m to 200 m (Figure 13) behind the seawall that could have reflected back the tsunami, increased the inundation depth behind the seawall and dragged the seawall and the ruins to the sea side. During the survey, the positions of the ruins were documented. The schematic positions of the original seawall and the ruins are given in Figure 12. The cross-section was measured along the original seawall position at every 4 m distance. The location of the seawall and the surrounding area are presented in Figure 13.

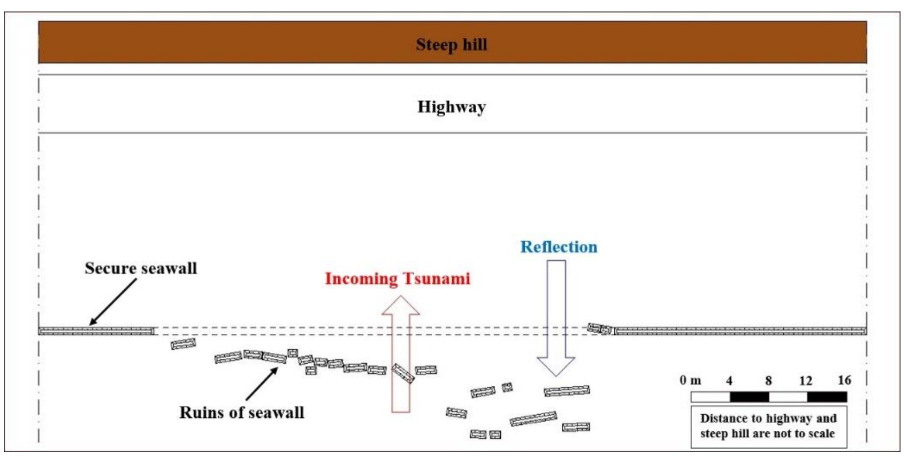


Figure 12. Schematic of seawall and ruins positions

Figure 13. Seawall position and the surrounding area (map from Google Earth Image)

As can be seen in Figure 12, the ruins of seawalls were found in front of the seawall original position at the beach side. It indicates that the debris were dragged seaward during tsunami run-down. In Figure 12, it can be seen that the debris were scattered with the longest distance of the debris from its original position was approximately 10 m. Actually, this is the preferred condition for a ruined seawall since, the dragging of debris seaward is expected not to harm anyone or buildings in the sea. Since seawalls are normally built along the coast to protect the beach from erosion, it is important to understand the failure mechanism which dictates the direction of the debris when the seawall is destroyed by tsunami.

2.2 Simulation of seawall destruction mechanism

A laboratory experiment was conducted to investigate the mechanism of seawall damage by the tsunami along Sunda Strait at Banten. The experiment was conducted at Gadjah Mada University, Indonesia. The tsunami surge was simulated based on dam break model. Such model has been used by many such as (Triatmadja and Nurhasanah 2012, Triatmadja and Benazir 2014). The validity of such method to simulate tsunami surge was discussed by (Kuswandi and Triatmadja 2019). The flume that was used for the simulation was 0.6 m wide, 0.4 m deep, 12 m long which was equipped with a quick release mechanism to generate tsunami surge. Water level probes were installed along the flume. A set of cemented seawall model was installed in and perpendicular to the flume. A block of the cemented seawall was modeled or represented by an acrylic of 0.06 m high, 0.016 m wide at the bottom and 0.015 m wide at the top. The seawall model scale was 1:20. The length of each element was 0.05 m. Each element can be placed next to the other elements to form a 0.60 m of seawall model perpendicular to the flume. The connection between seawalls can be strengthened using wedges. The wedges lengths can be varied to simulate the strength of the seawall to be modeled. The tsunami flume with tsunami generation (dam break) facility is presented in Figure 14. The scheme of seawall model test is given in Figure 15.

Figure 14. The flume equipped with dam break generation facility

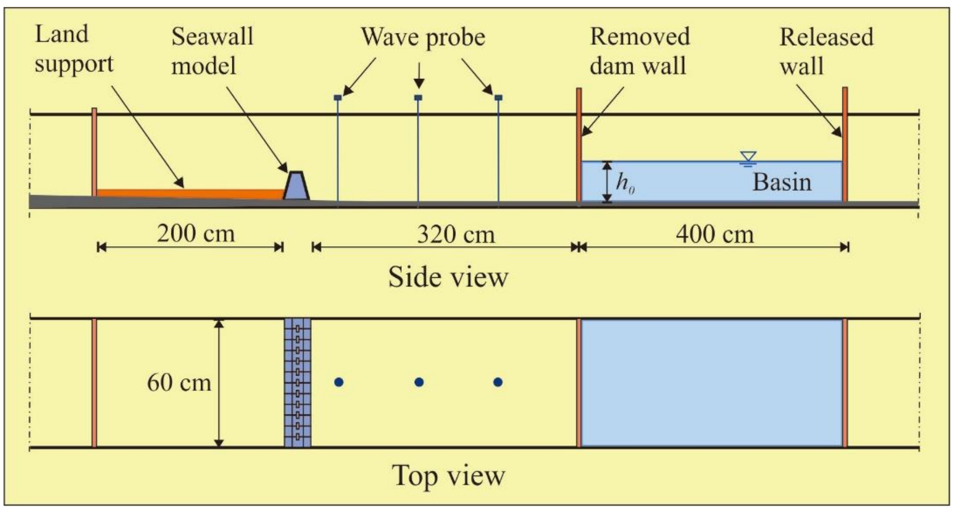


Figure.15. Schematic of seawall model test

Based on the field condition, a seawall model was set as follows. The seawall model was set perpendicular to the flume. At the boundary (flume walls) the seawall was fixed to simulate the undestroyed part in the field. In order to simulate the strength of the seawall, the wedges that connected the seawall was varied. These were 0.0 m (without wedge), 0.014 m, 0.021 m, and 0.028 m long. After the seawall was set, tsunami surge was generated from the upstream by lifting the gate that separate the flume into two parts. The upstream part was the basin that represent the source of tsunami. As the gate was lifted, the water in the basin surged toward the seawall model. The water depth of the basin was varied to create various tsunami inundation depths and forces on the seawall model.

3. RESULTS AND DISCUSSION

Prior to the hydrodynamic simulation, the seawall (cemented seawall) model strength was observed. This was conducted by a pull-out experiment that was aimed to observe the seawall model's strength under uniform static force. The sketches of the pull-out test are presented in Figure 16. The wedges that linked between two loose seawall element models are shown as small brown rectangles. The results of the loading tests for various wedge lengths are presented in Table 1.

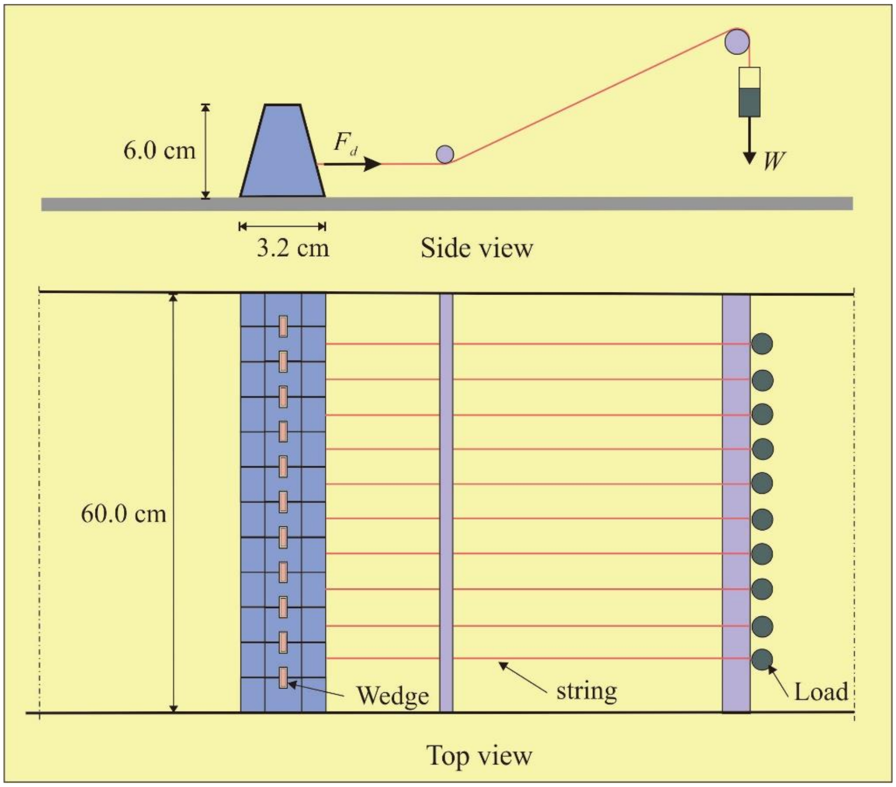


Figure 16. Schematic of pull out test

Table 1. Maximum (failure) loads of various wedge lengths

Wedge Length (cm)	Load at failure (N)
0	16.1
1.4	27.2
2.1	30.0
2.8	Not available

The strengths of the seawalls as described in Table 1 are not scaled to the real strength of the seawall however, they are needed to indicate the hydrodynamic force of the surge as they failed to withstand the tsunami force. This is because it is not possible to measure such force in the experiment using load cell since the seawall model should be kept fixed in place while the deformation may occur prior to the collapse. Computation of tsunami force based on Equation 1 may not bring a correct answer because, in reality the tsunami will overtop and overflow the seawall and hence the calculated force will be significantly higher than in reality. Using Table 1, the tsunami surge force on the seawall can be approximated based on the maximum load.

The experiment of the tsunami attack on seawall structure is presented in Figure 17. The first model was tested where the model was placed on top of the flume bed and no land support behind the wall. In this case, the seawall under the test would finally be damaged and was dragged landward. As can be seen in Figure 18, the broken seawall was dragged landward. The second model was tested where the seawall was supported by land of approximately 40% of the wall height (0.024 m). As indicated in Figure 19, the seawall was stable against the incoming tsunami. However, during run down, the seawall was destroyed and the debris was dragged seaward. Figure 19 shows the conditions of the seawall model after tsunami attack where the surge depth was 3.1 cm. It was the return flow or the run down that destroy the seawall. Hence the debris was dragged into the sea.

Tsunami force on the seawall model could be computed by equation proposed by (Triatmadja and Nurhasanah 2012) and presented as Equation (1).

$$F = C_f \, \rho(1-n^2)BhU^2 \tag{1}$$

where C_f is a coefficient equals 1.03, ρ is the density of water, *n* is the ratio of the opening to the total area, *B* is the width of the building, *h* is the surge front depth and *U* is the front celerity ($U = 2\sqrt{gh}$).

The seawall conditions with no land support after tsunami attack are presented in Table 2. The ratio between the forces that destroy the seawall (calculated based on Equation 1) and the maximum load during pull-out tests are given in Table 2. It can be seen that the ratio varies from 0.78 to 1.45 when the seawall was destroyed. This indicates that Equation 1 may sometime slightly under predict or over predict the force. One of the reasons is that the tsunami, in this case, overtopped the model where Equation (1) is no longer valid.

(a) The tsunami hit the seawall

(b) The seawall was damaged by tsunami

Figure17. Simulation of seawall destruction due to tsunami

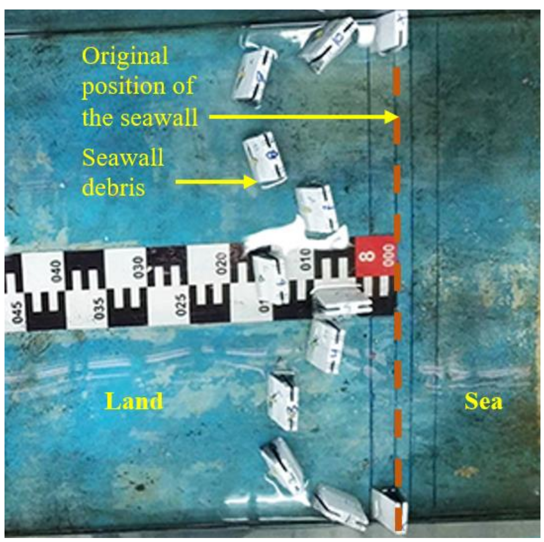
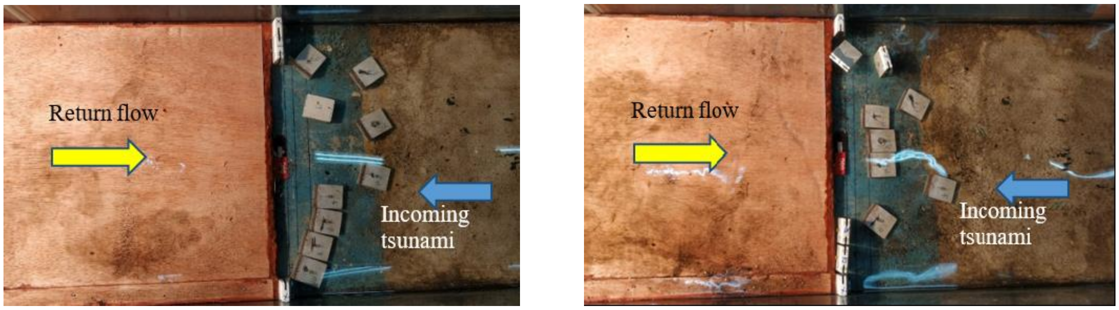


Figure 18. Debris of seawall were dragged landward, no land support behind the seawall



(a) Without wedges (b) With wedges of 1.4 cm

Figure 19. Seawall condition after wave attack (with land support)

Table 2. The seawall conditions under tsunami attack, no land support behind the seawall

Wedge length (cm)	Surge front height 1.9 cm		2.8 cm		3.1 cm	
	Final Condition	(Calculated force)/ (Maximum pull out force)	Final Condition	(Calculated force)/ (Maximum pull out force)	Final Condition	(Calculated force)/ (Maximum pull out force)
0	Secured	0.54	73% damaged	1.18	90% damaged	1.45
1.4	Secured	0.32	Bending and 47% damaged	0.7	80% damaged	0.86
2.1	Secured	0.29	Bending and 40% damage	0.63	70% damaged	0.78
2.8	Secured	-	bended (max.=7 cm)	-	bended (max.=7 cm)	-

Pull-out force creates almost total damage

4. CONCLUSION

Seawalls that are designed to protect the beach from erosion may not be able to withstand tsunami force. The destruction of the seawall can be caused by hydrodynamic force as well as impact force of boulder or debris material that hit the seawall during tsunami attack. Seawall debris as a result of tsunami attack may endanger other buildings and people. The direction of the seawall debris depends on whether it was the run-up or the run-down hydrodynamic force that destroy the seawall.

Based on the laboratory experiment, Equation 1 produced forces in the range between 70% to 150% of the maximum force that destroy the seawall. Sufficient land support behind the seawall, in our case approximately 40% of the seawall height, may held the seawall in place and avoid the destruction during run up. However, such seawall may be destroyed by the hydrodynamic force during tsunami run-down.

These mechanisms of destruction that determine the direction of the seawall debris are relevant to tsunami mitigation. Possible tsunami return flow (run down) is important for consideration since, normally tsunami is a wave train that attacks the beach in a series.

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