ISSN 2541-223X

MODELING OF TSUNAMI RUN-UP ONTO SLOPING BEACH AND ITS INTERACTION WITH LOW STRUCTURE

Benazir[1*], Radianta Triatmadja[1], Adam Pamudji Rahardjo[1], Nur Yuwono[1]

[1]*Department of Civil and Environmental Engineering, Gadjah Mada University, Indonesia*

ABSTRACT

Run-up process in tsunami phenomenon is one of other variables which affect destructions and damages in inland. In order to study the interaction between tsunami surge and low structure, it is convenient to conduct numerical modeling with a robust model. Mathematical analysis of the run-up problem usually leads to expansion solutions for certain types of waves such as shallow water waves. The tsunami model used in this research is based on the non-linear shallow water theory and the constant grids. Physical modeling is performed to validate the results of numerical model where series of simulations were conducted in wave flume of 15.90 m long, 0.60 m wide, and 0.44 m high that was facilitated with a tsunami generator based on dam break system. The flume is divided as a reservoir along the 7.90 m and downstream as observation area which is separated by a gate. The reservoir depth is varied on 0.30, 0.25, 0.20, and 0.15 m and 0.10 m for downstream water depth as initial bore evolution. A sloping beach is 1:20 vertical to horizontal. The square model is placed at 1.60 m in front of the gate and the dimension of model is varied on 0.10x0.10 m and 0.15x0.15 m of long and width, respectively. In attempting to study the run-up characteristic and the interaction of tsunami surge when overtopped to building, it is essential to focus the research scope to the run-up form and maximum inundation in inland. Based on the investigation, both mathematical and physical model yielded a good approximation to predict the run-up and maximum inundation inland. The effect of low building is dependent on its dimension. The larger volume of the low building caused the lower of run-up height.

Keywords: Inundation; Simulation; Structure; Submerged; Tsunami

1. INTRODUCTION

Indonesia is prone to earthquake occurrences that generate tsunami due to its tectonic setting. The archipelago has a unique region which is surrounded by the complexity of tectonics and plate boundaries, owing to the confluence of multiple plates moving at very high relative speeds (McCarffrey, 2009). Therefore, Lavigne et al. (2007) stated that around 75% of Indonesian coastline is under threat from tsunami attack. Either earthquake or tsunami is the most devastating hazard which depends on their scale. Both phenomena have significant destructions but tsunami is the one that gives great loss of live in recent years. For the threat of tsunami in the future, an integrated hazard mitigation should be developed.

[*]Corresponding author's email: benazir_27iska@yahoo.com

Figure 1 A modest house was placed in the coastal area that was reconstructed after tsunami 2004 in Banda Aceh

Synolakis et al. (2005) classified that tsunami hazard mitigation is divided by detection, forecasting, and emergency preparedness. An understanding of the crucial characteristics of flooding is required such as run-up variable (see Fig. 2). Run-up is the maximum vertical elevation of a point located on initially dry land that is inundated by the waves (Synolakis et al., 2005). The devastating tsunami not only depends on height and surge velocity but also on the coastal morphology. The mild slope allows tsunami to propagate further into the mainland and it causes great damage. Meanwhile, the steep slope provides to reach higher run-up. Run-up is the essential parameter of tsunami form which directly related to the inland destructions.

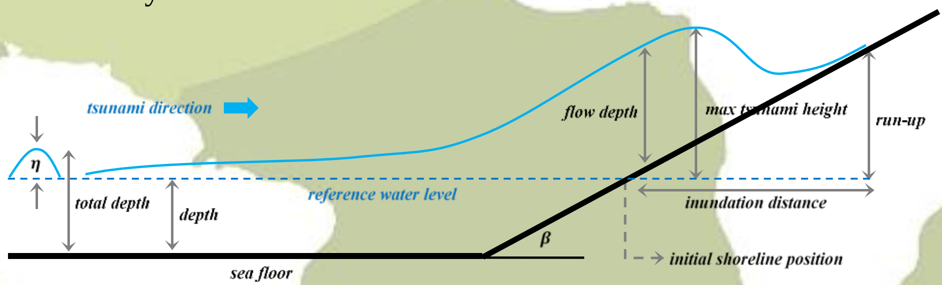

Figure 2 Sketch of tsunami terminology for the wave climbing up a sloping beach

This paper briefly discuss about crucial characteristic of tsunami flooding inland such as run-up, inundation, and flow depth that are required in emergency preparedness. Also, the interaction of tsunami surge with low structure is simulated using both numerical and physical modeling.

2. MATERIALS AND METHODS

2.1. Literature Review

Synolakis (1987) used the shallow water wave equations to solve run-up problem on a sloping beach. Based on his work on physical model, one equation, also known as run-up law, is derived.

$$\frac{R}{d} = 2.831\sqrt{cot\beta}\left(\frac{H}{d}\right)^{1.25} \quad (1)$$

In the Eq. (1), R refers to run-up height, d is the undisturbed water depth, H is wave height at shore, and $cot\ \beta$ is the slope angle. The higher tsunami height or the longer its wave period, the greater the volume of water carried onshore and the greater the extent of flooding area. Hill & Mader (1997) proposed a formula to calculate the maximum distance that run-up can penetrate inland on a flat coast.

$$X_i = H^{1.33} n^{-2} k \tag{2}$$

Where X_i is the limit of landward incursion, n is manning roughness, and the constant k has been evaluated for many tsunami and has a value of 0.06. The equation assumes that the run-up height equals to the maximum depth of tsunami at shore. Also, it indicates that the effect of tsunami can be minimized if the shore has a higher roughness coefficient.

2.2. Research Methodology

Mathematical analysis of the run-up problem usually leads to expansion solutions for certain types of waves such as shallow water waves. For the comparison of physical results, a mathematical computation simulated the same case using the main program of Imamura et al. (2006) and Goto et al. (1997). The program was slightly modified for interface concerns by Visual Basic .NET programming language. Flowchart of tsunami simulation using this program is shown in Fig. 3. The program uses second-order explicit leap-frog finite difference scheme to discretize a set of Nonlinear Shallow Water Equation (NSWE). For the propagation of tsunami in the shallow water, the horizontal eddy turbulence terms are negligible as compared with the bottom friction. The equations are written in Cartesian coordinate as (Imamura et al., 2006):

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{3a}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{\tau_x}{\rho} = 0 \tag{3b}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{\tau_y}{\rho} = 0 \tag{3c}$$

$D = h + \eta$ is the total water depth, where h is the still water depth and η is the sea surface elevation. M and N are the water velocity fluxes in the x and y directions, respectively:

$$M = \int_h^\eta u dz = u(h+\eta) = uD \tag{4a}$$

$$N = \int_h^\eta v dz = v(h+\eta) = vD \tag{4b}$$

Bottom friction in the x and y direction are respectively represented by terms τ_x and τ_y, which is function of friction coefficient f. This coefficient can be computed from Manning roughness n by the following relationship.

$$n = \sqrt{\frac{fD^{1/3}}{2g}} \tag{5}$$

Eq. (5) describes that the friction coefficient increases when the total water depth decreases. Manning roughness is usually chosen as a constant for a given condition of sea bottom and in this research $n = 0.012$ to represent the slope bottom made of plywood. The bottom friction terms are expressed by:

$$\frac{\tau_x}{\rho} = \frac{1}{2}\frac{f}{D^2} M\sqrt{M^2 + N^2} \tag{6a}$$

$$\frac{\tau_y}{\rho} = \frac{1}{2}\frac{f}{D^2} N\sqrt{M^2 + N^2} \tag{6b}$$

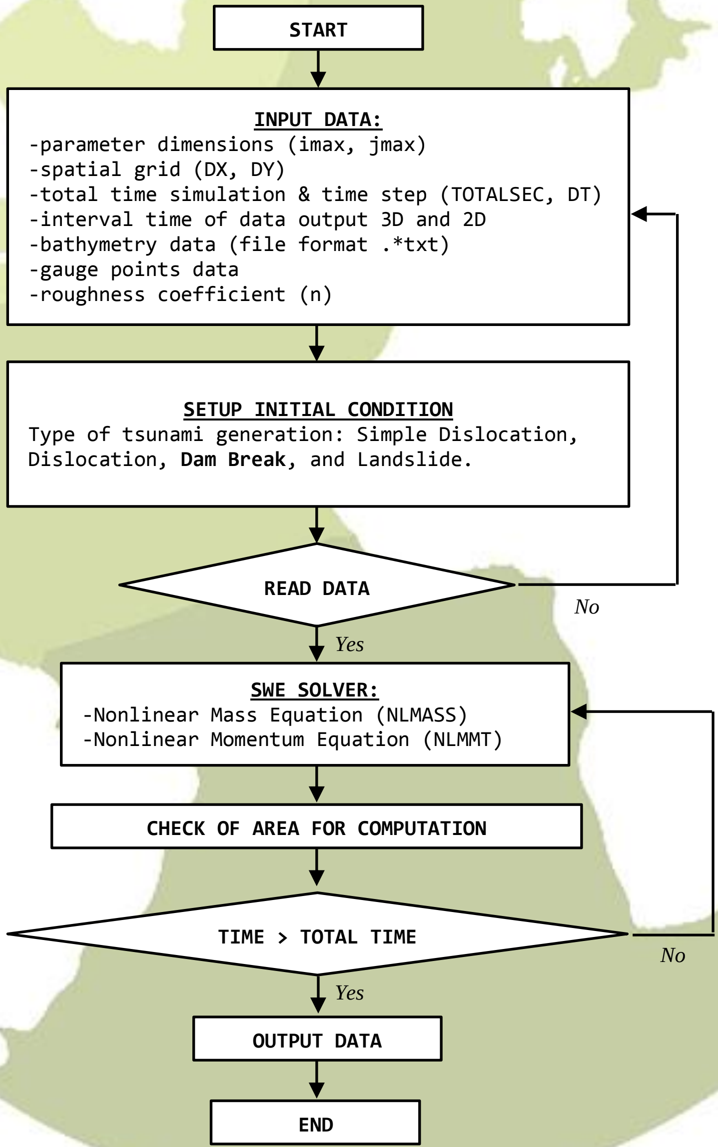

Figure 3 Flowchart of tsunami simulation using TUNAMI Modified (beta version)

Physical model was carried out in the Hydraulic and Hydrology Laboratory, Research Centre for Engineering Science, Universitas Gadjah Mada Indonesia (Fig.4). Physical modeling is performed to validate the results of numerical model where series of simulations was conducted in wave flume of 15.90 m long, 0.60 m wide, and 0.44 m high that was facilitated with a tsunami generator based on dam break system. The flume is divided as a reservoir along the 7.90 m and downstream as observation area which separated by a gate. The reservoir depth is varied on 0.30, 0.25, 0.20, and 0.15 m and 0.10 m for downstream water depth as initial bore evolution. A sloping beach is 1:20 vertical to horizontal. Square model was placed at 1.60 m in front of the gate and the dimension of model was varied on 0.10x0.10 m and 0.15x0.15 m of long and width respectively. The model was arranged in the wave flume either as single building. Four probe sensors were installed along the downstream side to measure wave height (H). The simulation was started by opening the divider gate vertically to produce tsunami bore on shallow water that finally run-up on land (downstream of the flume). The same method was carried out by Triatmadja & Benazir (2014). The interaction between the tsunami surge and the square building was recorded using a video camera.

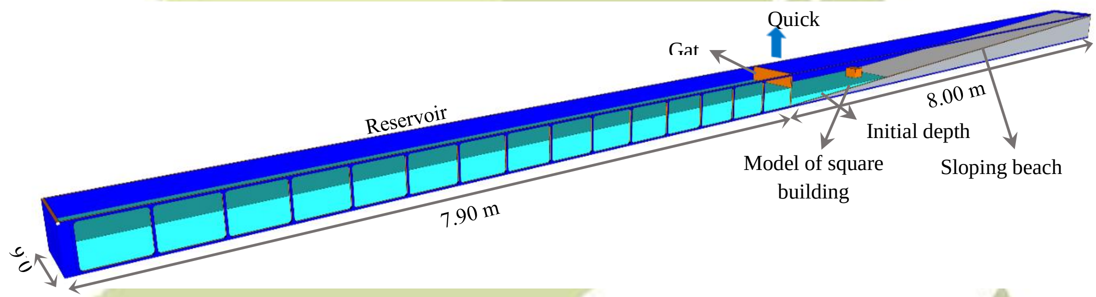

Figure 4 Experimental setup

3. RESULTS AND DISCUSSION

3.1 Tsunami Run-up on Sloping Beach

The performance of the maximum run-up was examined by varying water depth in the reservoir. The result of run-up height is given in Fig. 5. The run-up heights from numerical model were 0.172 m, 0.237 m, 0.302 m, and 0.368 m for reservoir depths of 0.15 m, 0.20 m, 0.25 m, and 0.30 m, respectively. These results show that simulation using numerical model provides fairly consistent results with the experiment data. A linear result is obtained from both simulations method where the higher reservoir depth provided the maximum run-up and vice versa. From Fig. 5, it may be said that the laboratory data agrees well with the numerical results especially for $d_0/d_1 > 2$. Meanwhile for $d_0/d_1 < 2$, the nonlinear effect becomes significant where the bore propagates in the finite depth. The numerical results are higher than the physical results. This condition is probably caused by the useof the uniform value of bottom friction coefficient along the slope model. However this variable is related to water level depth such as in Eq. (5), which states that the value of roughness becomes greater when the total depth is smaller if the Manning coefficient is constant and vice versa. Moreover, the run-up height is aslo affected by the initial downstream depth. The dry bed yields the higher value of run-up than non-zero of downstream depth as discussed by Benazir et al. (2016).

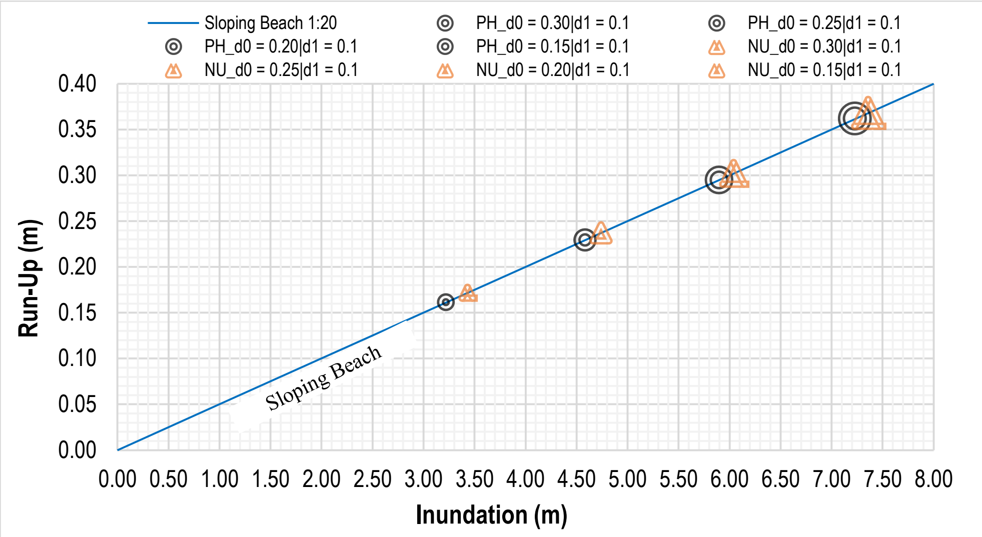

Figure 5 Relation between run-up and maximum inundation based on physical and numerical model. Higher d_0 is indicated by larger symbol

Figure 6 shows the results of the physical and numerical data and their relations with non-dimensional paramaters. The parameter H/d represents the wave height measured at 1 m downstream of the gate which d is undisturbed water depth and it has value of 0.05 m at the same location. Whereas, R/d is the undisturbed water depth at the instant run-up. The results have a good approximation compared to Eq. (1), especially for $H/d > 0.4$. For $H/d < 0.4$, the results are as predicted, which were described previously. Compared to the experimental setup, Synolakis (1987) generated a solitary wave form to approximate his theory (Eq. 1).

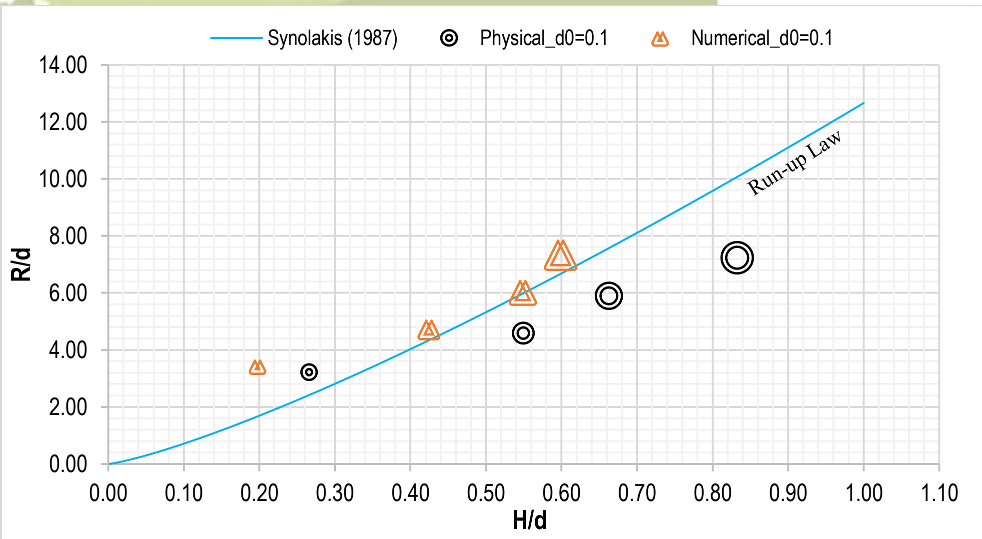

Figure 6 Relation between non-dimensional parameter R/d and H/d together with the run-up law (Eq. 1). Higher d_0 is indicated by larger symbol

There was completely different to present work where the dam break system was used. The dam break produced breaker waves. Based on visual observation for the slopes, waves, and initial depths used in this study, most of the waves broke as plunging breakers. This wave form represented as tsunami form when it reached shallow water

and the coast and also known as bore surge. Possibly owing to laboratory data in Fig. 6, there is a reason why these results were not linear compared to Eq. (1).
Predicted by Eq. (2), the roughness coefficients still play an important role in determining the maximum inundation, as seen in Fig. (7) below. Also, the formula calculates that the flow limit of landward incursion depends on tsunami height where recorded on shore. Compared with the investigation data, both numerical and physical data, have under predict the Eq. (2) yet. The differences are not significant for $H/d > 0.55$ of experimental data. However, the case of sloping beach did not match due to the flat slope as expected by Eq. (2). As described in Hills and Mayer (1997), that formula is derived to predict maximum distance where run-up can penetrate inland on flat coast. The coefficient of slope angle is not included.

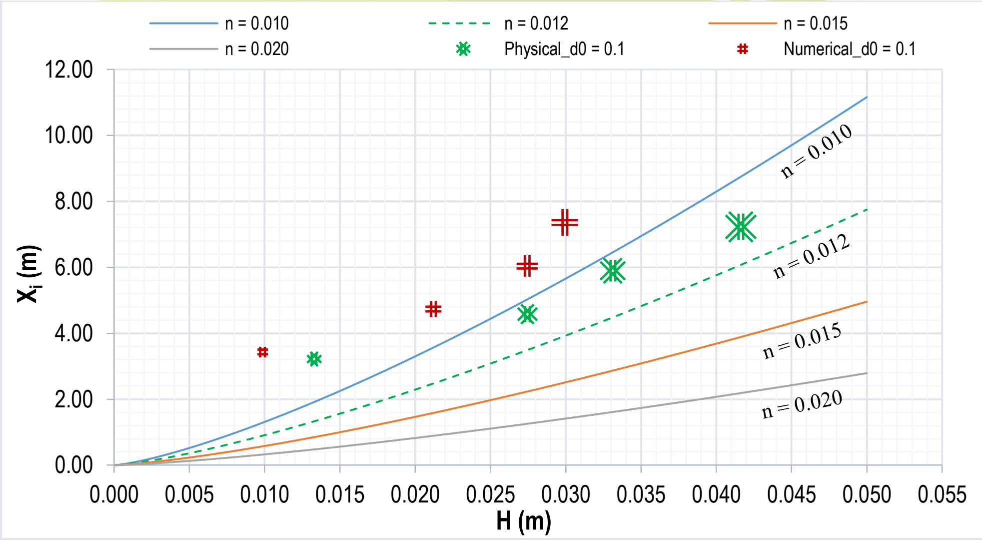

Figure 7 Inundation data versus estimated distance inundation by Eq. (2). Higher d_0 is indicated by larger symbol

3.2 Effect of the Square Building

The placement of the building in the coastal area may obstruct the tsunami flows. Such arrangement of buildings may reduce surge celerity and therefore, lessen destructions by the tsunami force. The wave energy is decreased when the surge interacts over the building which subsequently may minimize the surge to flow further inland. Such this event gives a positive reason that is considered to mitigation purposes. Even if the building do not withstand due to the tsunami attack, it would be the first to be damaged by the force of tsunami waves. When the building is collapsed, it may be drifted further inland, hits other buildings, and then creates more damage in urban area.
Based on Figure 8, either mathematical or physical model has a good consistency of run-up data by four variants of wave heights. Two types of building models were tested. The dimension of square building is taken an important role in determining the run-up height. The tested model indicated that the larger volume of the building reduced the run-up height. During the experiment, it was observed that the surges were deflected sideways by the building. The flow direction downstream of the building was not uniform across the channel due to the deflection by the building and the reflection by the

walls of the flume. The wall effect becomes higher when the dimension of the square building is greater.

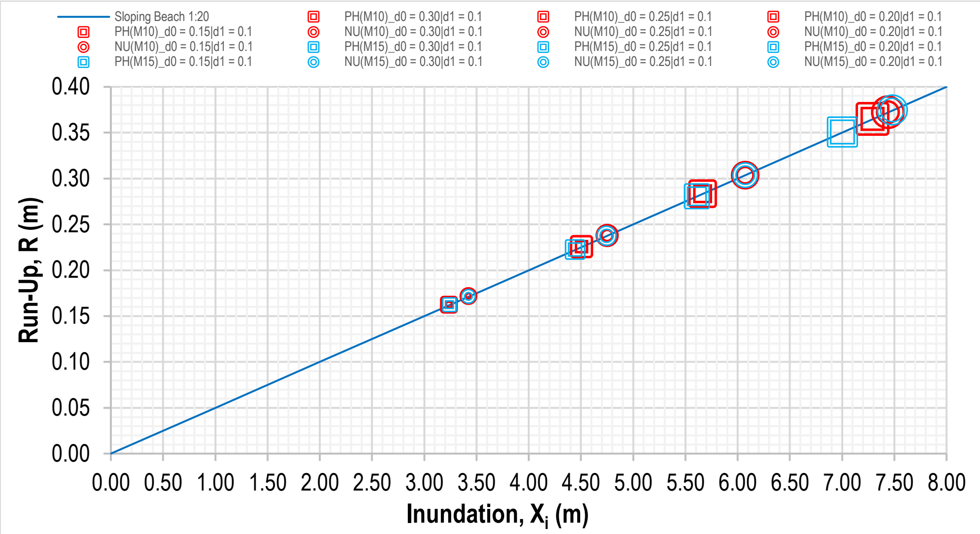

Figure 8 Effect of two types of square building over the run-up and inundation variable

It was expected that the dimension of the square building is an important factor that affected the run-up height and distance of inundation area. The reason for such a small effect to reduce the run-up height is that data was conducted using a limited height of the building, which was easily overtopped by the surge. The low building enables the tsunami to flows through where the building model is, thus is not significant enough to minimize the tsunami height.

4. CONCLUSION

Tsunami run-up on the sloping beach not only depends on the height and surge velocity but also the coastal morphology such as roughness and slope angle. There was not significant effect of low building to minimize run-up height where the surge easily overtop the building. The larger volume of the building is considered to reduce the distance of tsunami inundation further inland.

5. ACKNOWLEDGEMENT

The research was fully funded by Lembaga Pengelolaan Dana Pendidikan (LPDP) Kementerian Keuangan Republik Indonesia via Scholarship of Indonesia Education (BPI). We would like to express our sincere gratitude for the funding. The Hydraulic and Hydrology Laboratory of the Center for Engineering Science Universitas Gadjah Mada is acknowledged for its support throughout the physical modeling.

6. REFERENCES

Benazir, Triatmadja, R., Rahardjo, A.P., & Yuwono, N., (2016), Tsunami Run-up on Sloping Beach based on Dam Break System, to be presented in the 5th International Seminar of HATHI, 29-31 July 2016, Bali.

Goto, C., Ogawa, Y., Shuto, N., & Imamura, F., (1997), Numerical Method of Tsunami Simulation with Leap-Frog Scheme, IOC Manual: IUGG/IOC Time Project, UNESCO

Hills, J.G., & Mader, C.L., (1997), Tsunami Produce by the Impacts of small asteroids. Annals of the New York Academy of Science, Volume 822, pp. 381-394.

Imamura, F., Yalciner, A. C., & Ozyurt, G., (2006), Tsunami Modelling Manual (TUNAMI Model), Disaster Control Research Center Tohoku University, Sendai.

Lavigne, F. et al., (2007), Field Observations of the 17 July 2006 Tsunami in Java. Natural Hazard and Earth System Sciences, Volume 7, pp. 177-183.

McCaffrey, R., (2009), The Tectonic Framework of the Sumatran Subduction Zone. Annual Review of Earth and Planetary Sciences, Volume 37, pp. 345-366.

Synolakis, C. E., 1987. The Runup of Solitary Waves. Journal of Fluid Mechanics, Volume 185, pp. 523-545

Synolakis, C.E., Okal, E. & Bernard, E., (2005), The Megatsunami of December 26, 2004. The Bridge, Volume 35 Number 2, pp. 26-35.

Triatmadja, R. & Benazir, (2014), Simulation of Tsunami Force on Rows of Buildings in Aceh Region after Tsunami Disaster in 2004. Science of Tsunami Hazard, Volume 33 Number 3, pp. 156-169.