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COMPARISON OF METHODS FOR SIMULATING TSUNAMI RUN-UP THROUGH COASTAL FORESTS

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ABSTRACT

The research is aimed at reviewing two numerical methods for modeling the effect of coastal forest on tsunami run-up and to propose an alternative approach. Two methods for modeling the effect of coastal forest namely the Constant Roughness Model (CRM) and Equivalent Roughness Model (ERM) simulate the effect of the forest by using an artificial Manning roughness coefficient. An alternative approach that simulates each of the trees as a vertical square column is introduced. Simulations were carried out with variations of forest density and layout pattern of the trees. The numerical model was validated using an existing data series of tsunami run-up without forest protection. The study indicated that the alternative method is in good agreement with ERM method for low forest density. At higher density and when the trees were planted in a zigzag pattern, the ERM produced significantly higher run-up. For a zigzag pattern and at 50% forest densities which represents a water tight wall, both the ERM and CRM methods produced relatively high run-up which should not happen theoretically. The alternative method, on the other hand, reflected the entire tsunami. In reality, housing complex can be considered and simulated as forest with various size and layout of obstacles where the alternative approach is applicable. The alternative method is more accurate than the existing methods for simulating a coastal forest for tsunami mitigation but consumes considerably more computational time.

Keywords: modeling; long wave; vegetation; greenbelt; density; layout; dam break.

1. INTRODUCTION

Indonesia has suffered from many tsunami disasters, especially in Sumatera Island. After the destructive tsunami attacked at Aceh and Nias Island in 2004, several mitigation methods have been implemented such as the development of evacuation routes, construction of escape buildings, relocation of victim houses, and the utilization of buffer zones along the coastal areas. The buffer zone with relatively densely populated vegetation may be classified as a permeable structure prevention. Nowadays, this method is widely implemented at vulnerable tsunami regions due to its relatively low cost and ease of maintenance.

A sustainable buffer zone (coastal forest) requires suitable vegetation for tsunami prevention system. Mangrove as a natural barrier against tsunami is not suitable for sandy beaches and it grows only in the estuary area (Hiraishi & Harada, 2003). On the contrary, the *Casuarina Equisetifolia* species has been proven suitable for sandy beach type such as along Pacitan Bay in southern Java Island (Muhari et al., 2012). A similar buffer zone can be found along Geureute Valley in Aceh Jaya District as shown in Figure 1. Another type of coastal vegetation is *Cocos Nucifera* (coconut palm) which is commonly grown in tropical areas.

Figure 1. Coastal vegetation at Aceh Jaya District (Source: Google Earth captured on September 29th, 2015)

The devastating tsunami power depends on the height and the surge velocity, whilst the coastal morphology affects the extent of such power on land. A mild slope beach allows the tsunami to propagate further inland and may create great damage. The land use, especially with relatively dense vegetation, has also an important role in protecting the beach against run-up and inundation. The degree of such protection depends on tsunami scale. A large scale of tsunami attack such as the Indian Ocean Tsunami 2004 at Banda Aceh, was capable of uprooting a lot of coastal vegetation resulting in further inland inundation. During Tsunami 2004 disaster, the maximum tsunami run-up was recorded at Leupung Beach, Aceh Besar District. Shibayama et al. (2005) reported that the highest run-up reached 49.43 m in Ritieng Hill. This event was verified by Lavigne et al. (2009) where their post-survey yielded 51 m at the same location. In the absence of forest protection, the tsunami could have been even more severe.

Forbes & Broadhead (2007) mentioned that the effectiveness of tsunami mitigation offered by various types of coastal forests depends on a number of parameters including forest width, tree density, age, tree diameter, tree height, and species composition. Therefore, a quantitative evaluation of coastal forest effectiveness against tsunami, especially in term of run-up and inundation, is required for mitigation purposes. This can be done by using numerical simulation.

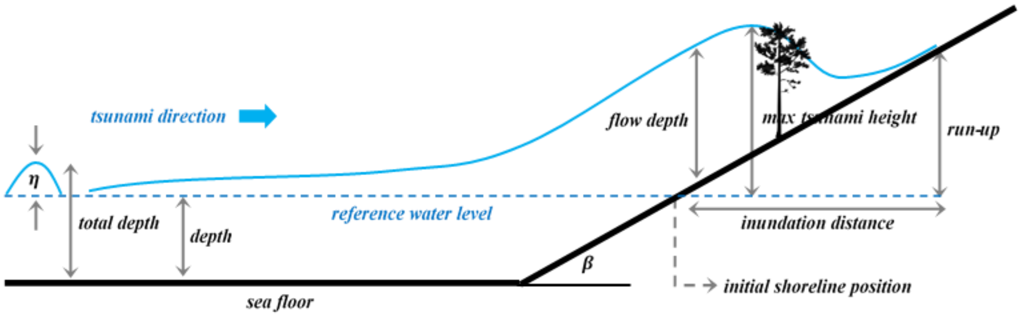


Figure 2. Sketch of tsunami run-up climbing up a sloping beach (the terminology is based on UNESCO-IOC)

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) as illustrated in Figure 2 and is the essential parameter of tsunami hazards that directly related to inland destructions. Synolakis (1987) used the shallow water wave equations to solve run-up problem on a sloping beach. He derived a run-up law based on the physical model as shown in Eq. (1).

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

In Eq. (1), R refers to run-up, d is the undisturbed water depth, H is wave height at the shore, and β stands the slope angle. Eq. (1) may be used for a first approximation of tsunami run-up but a comprehensive run-up study involving coastal land use such as the existence of coastal forest using numerical simulation is required to determine more accurate run-up. A number of tsunami run-up against coastal forests have been carried out for example by Harada & Kawata (2004) and Yanagisawa et al. (2009). Basically, the effect of the forest was represented by using the Manning roughness coefficient. Higher roughness coefficient represents higher density of the forest. Despite their usefulness and efficiency in term of computer time, representing a forest barrier by Manning roughness coefficient seems to have a drawback. The effect of the trees layout within the forest and the effect of reflection may not be properly simulated which in turn may result in significantly different run-up patterns and height. In this paper, an alternative method of modeling coastal forest or similar barrier against tsunami run-up is proposed. The performance of the method is compared with the other existing methods i.e. CRM and ERM methods.

2. TSUNAMI PROPAGATION THROUGH A FOREST

Mathematical models based on a set of Nonlinear Shallow Water Equation (NSWE) has been widely used for tsunami simulation. A notable program that used second-order explicit leap-frog finite difference scheme to discretize a set of NSWE was developed by Goto et al. (1997) and Imamura et al. (2006). We rewrote the program in Visual Basic .Net where some additional input-output facilities were added for convenience. The shallow water equations in Cartesian coordinate are as follows Imamura et al. (2006).

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \qquad (2a)$$

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

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

$D = h + \eta$ represents the total water depth, where h stands for the still water depth and η denotes the sea surface elevation. M and N are the mass fluxes in the x and y-direction, respectively.

$$M = \int_h^\eta u dz = u(h+\eta) = uD \tag{3a}$$

$$N = \int_h^\eta v dz = v(h+\eta) = vD \tag{3b}$$

Bottom friction in the x and y-direction are respectively represented by terms τ_x and τ_y, which is a function of friction coefficient f. This coefficient can be computed from Manning roughness (n_0) by the following relationship.

$$n_0 = \sqrt{\frac{fD^{1/3}}{2g}} \rightarrow f = \frac{{n_0}^2 2g}{D^{1/3}} \tag{4}$$

Eq. (4) 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 the land surface. The bottom friction terms are expressed by:

$$\frac{\tau_x}{\rho} = \frac{1}{2}\frac{f}{D^2} M\sqrt{M^2 + N^2} \tag{5a}$$

$$\frac{\tau_y}{\rho} = \frac{1}{2}\frac{f}{D^2} N\sqrt{M^2 + N^2} \tag{5b}$$

2.1. Constant Roughness Model

The Constant Roughness Model (CRM) which represents the effect of coastal forest based on Manning roughness coefficient (n_0) is widely used. Aida (1997), Kotani et al. (1998), and Latief & Hadi (2007) used Manning coefficients of 0.040, 0.030, and 0.048, respectively for the coastal forest. The variation of the above roughness coefficient suggests that the Manning coefficient representing coastal forest is site specific.

2.2. Equivalent Roughness Model

Petryk & Bosmajian (1975) introduced an important concept to present the Manning roughness form as hydraulic resistance. Based on their concept, Goto & Shuto (1983) and Aburaya & Imamura (2002) developed the ERM method where the equivalent roughness (n_e) can be defined by the following equation.

$$n_e = \sqrt{D^{4/3}\frac{C_D}{2gd_i}\frac{\theta}{100-\theta} + {n_0}^2} \tag{6}$$

where d_i and θ stand for the tree diameter and the percentage of the bottom area occupied by the trees in a grid on the numerical domain, respectively and C_D as drag coefficient. USAC (1984) stated that C_D value is a function of Reynolds number (R_e).

$$C_D = 1.2 \quad \text{if} \quad R_e \le 2\times 10^5 \tag{7a}$$

$$C_D = 1.2 - 0.5\left(\frac{R_e}{3\times 10^5} - \frac{2}{3}\right) \quad \text{if} \quad 2\times 10^5 \le R_e \le 5\times 10^5 \tag{7b}$$

$$C_D = 0.7 \quad \text{if} \quad R_e \ge 5\times 10^5 \tag{7c}$$

FEMA (2003) suggested that the drag coefficient values should be between 1.25 and 2, depending on the ratio between the width of a model and the flow depth. Yanagisawa et al. (2009)

also defined the C_D value in Eq. (6) based on their investigation among several species such as *Rhizophora sp*. and *Bruguiera sp*. Eq. (6) accommodates both the resistance force due to the forest and the bottom friction to land use condition. The Equivalent Roughness Model (ERM) has been used by Harada & Imamura (2000) to model tsunami propagation through a forest. It uses the resistance of the coastal forest to represent the equivalent roughness. Besides that, Koshimura et al. (2009) and Muhari et al. (2011) also implemented this method to simulate tsunami through spaces between buildings at coastal area.

2.3. The Alternative Model for Tsunami Propagation through Forest

The effect of a forest on tsunami propagations is reflection over the trees' trunk and flow deceleration due to friction against the surface of the trees trunks, branches, and leaves. In the model, the trees can be represented using hypothetical columns for simulating the reflection. The effect of the friction against the surface of the trees' trunks can be represented by using the Manning roughness coefficient. Therefore, the proposed alternative method for simulating the propagation of tsunami through a forest is by using a Manning roughness coefficient as if there is no forest, but all the trees were simulated as vertical square columns. The size of the columns are equals to the size of the trees' trunk or slightly larger to accommodate the effect of the branches and leaves.

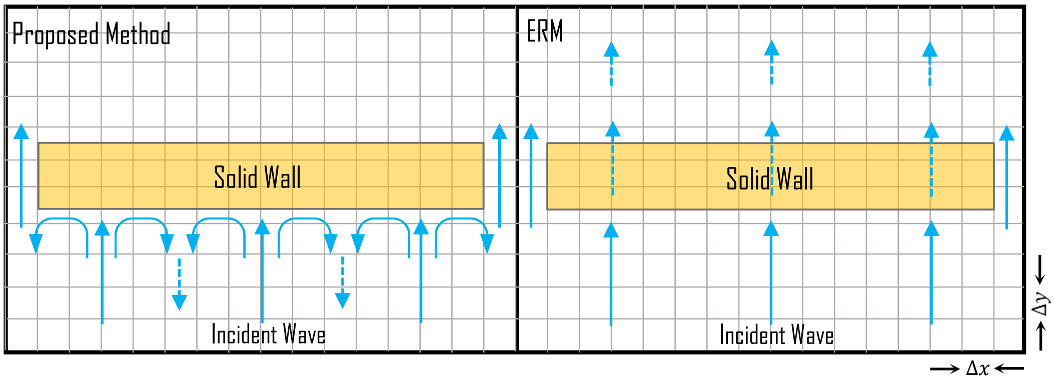


Figure 3. An extreme situation that shows the difference between the alternative method and the ERM method.

The alternative method resulted in the changes of the flow direction because of the coastal forest whereas the CRM and ERM methods reduce the flow through the coastal forest due to the use of equivalent roughness. The effect of a solid wall as illustrated in Figure 3 clearly shows the difference between the proposed alternative method and the existing methods. The figure shows that the alternative model accommodates the total reflection process without run-up downstream whilst the ERM method somehow produces run-up downstream of a solid wall.

3. RESEARCH PROCEDURE

The numerical model was applied to simulate a physical model of tsunami run-up on a 1:20 sloping beach in a flume for comparison. The flume was 15.00 m long x 0.60 m wide x 0.44 m high. The flume area was divided into two sections where the upstream part was a 4 m long reservoir (l_0) of 0.20 m deep (d_0) that was used as tsunami source whilst the downstream was a sloping beach model. The tsunami was generated by using a dam break system as used by Chanson (2005), Triatmadja & Nurhasanah (2012), and Triatmadja & Benazir (2014). At the downstream area, until 3 m downstream of the gate the initial depth (d_1) was 0.10 m after which the water depth decreased due to the beach slope. Hence, the shoreline was 5 m downstream of the gate. The arrangement of the model is depicted in Figure 4.

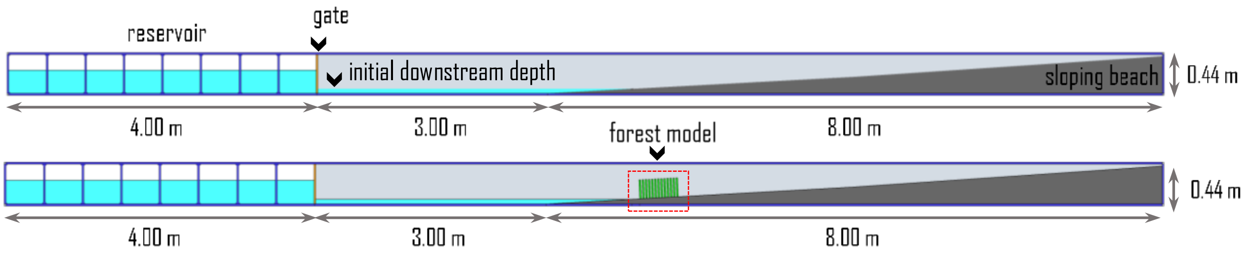


Figure 4. Arrangement of tsunami simulation

The physical model has been carried out and was reported as shown in Figure 4 in Benazir et al. (2016A) and (2016B).

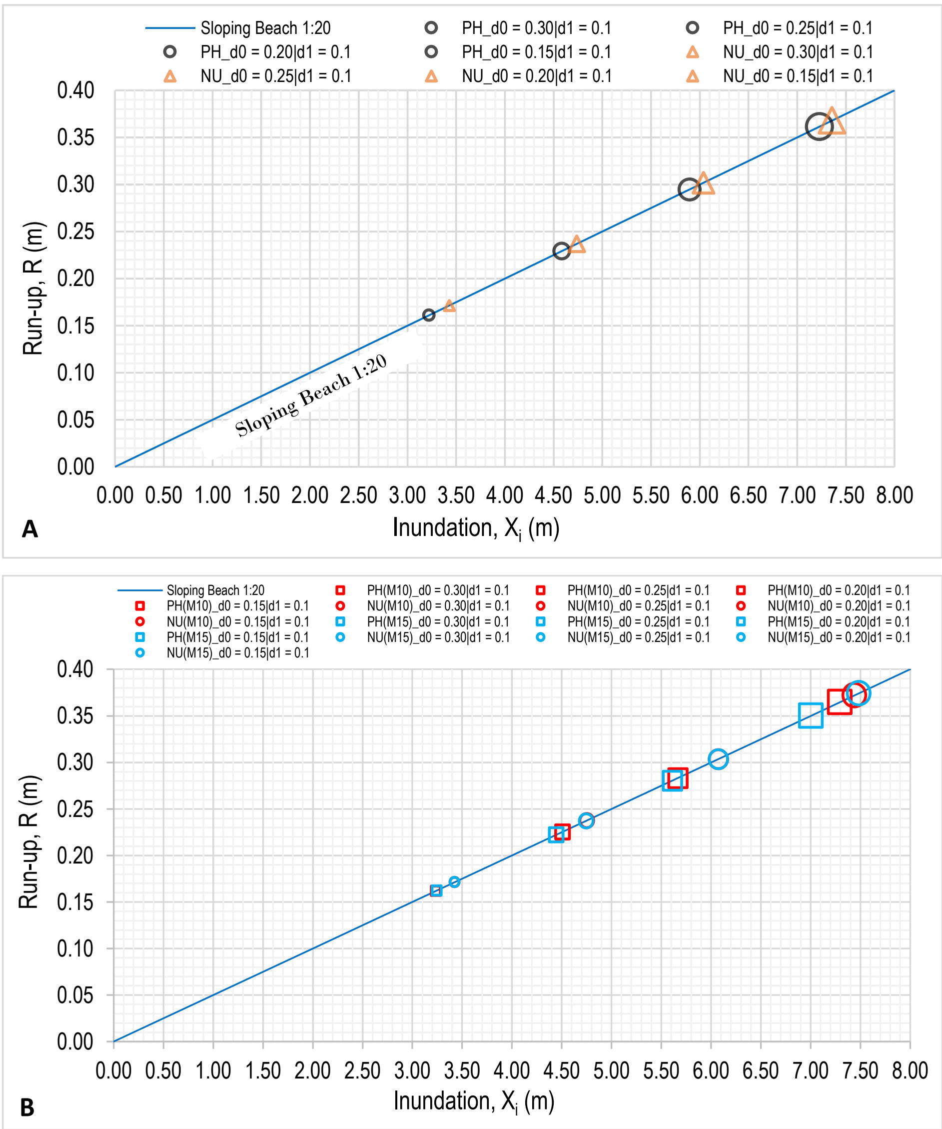
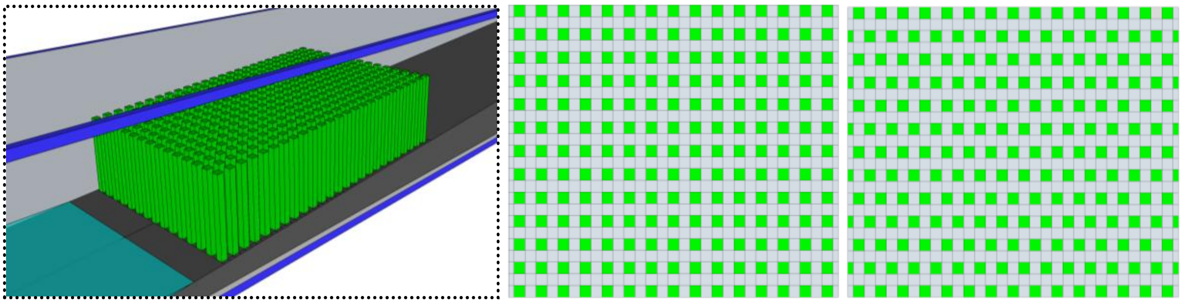


Figure 5. (A) The relation between run-up and maximum inundation and (B) the effect of the building against run-up based on the physical and numerical model. Higher d_0 and larger buildings are indicated by larger symbol (Benazir et al. (2016A) and (2016B))

These results showed that the numerical model provides fairly consistent results with the experimental data as indicated in Figure 5A. Besides that, the dimension of the square building was found to be an important factor that affected the run-up height and the distance of the inundation (Figure 5B). These findings confirmed that the numerical model results produced fairly accurate tsunami run-up with or without obstacles on a sloping beach and hence may be used with confidence to examine the tsunami run-up against the hypothetical coastal forest model.

3.1. Hypothetical Model of Coastal Forest

In order to evaluate the performance of the ERM method, CRM method and the proposed alternative method, hypothetical forests of different densities and trees layout were selected for simulations. The hypothetical forests model consisted of uniform square columns that represent the trees that were high enough and above the tsunami water surface. The dimension of the model of the tree was 0.02 m by 0.02 m. The hypothetical model layout is shown in Figure 6A. The densities of the forests depend on the total area of the trees relative to the area of the forest.



A. 3D view of Hypothetical model *B. Uniform layout* *C. Zigzag layout*

Figure 6. The hypothetical model of coastal forest and its layout variations

The parameters for the simulation were given in Table 1. During the investigation, two layout conditions were tested (Figure 6B-C). Both the uniform and the zigzag layouts have a total of 195 trees at G = 0.02 m and 90 trees at G = 0.04 m. The forests model front rows were at 0.10 m from the shoreline.

Table 1. The model of hypothetical coastal forest

Length (m)	Width (m)	Diameter (m)	Gap (m)	Density	Layout
0.50	0.60	0.02	0.02	25%	uniform & zigzag
0.50	0.60	0.02	0.04	11%	uniform & zigzag

4. RESULT AND DISCUSSION

4.1. Tsunami Propagation on Sloping Beach without Forest Model

A typical tsunami heights at the shallow water region and at the land region are shown in Figure 7A. The relative tsunami height (H/d_o) was approximately 0.22 at 1 m from the source or X_i = -4 m seaward from the shoreline model. Along the horizontal bottom of the flume (X_i = -5 m to -2 m) the tsunami height fluctuated with time as can be seen in Figure 7A. The total depth and the maximum tsunami height at certain points along the flume which occurred at different time are shown in Figure 7B. The solid line connecting each of the maximum tsunami height indicates the envelope of maximum tsunami height along the flume.

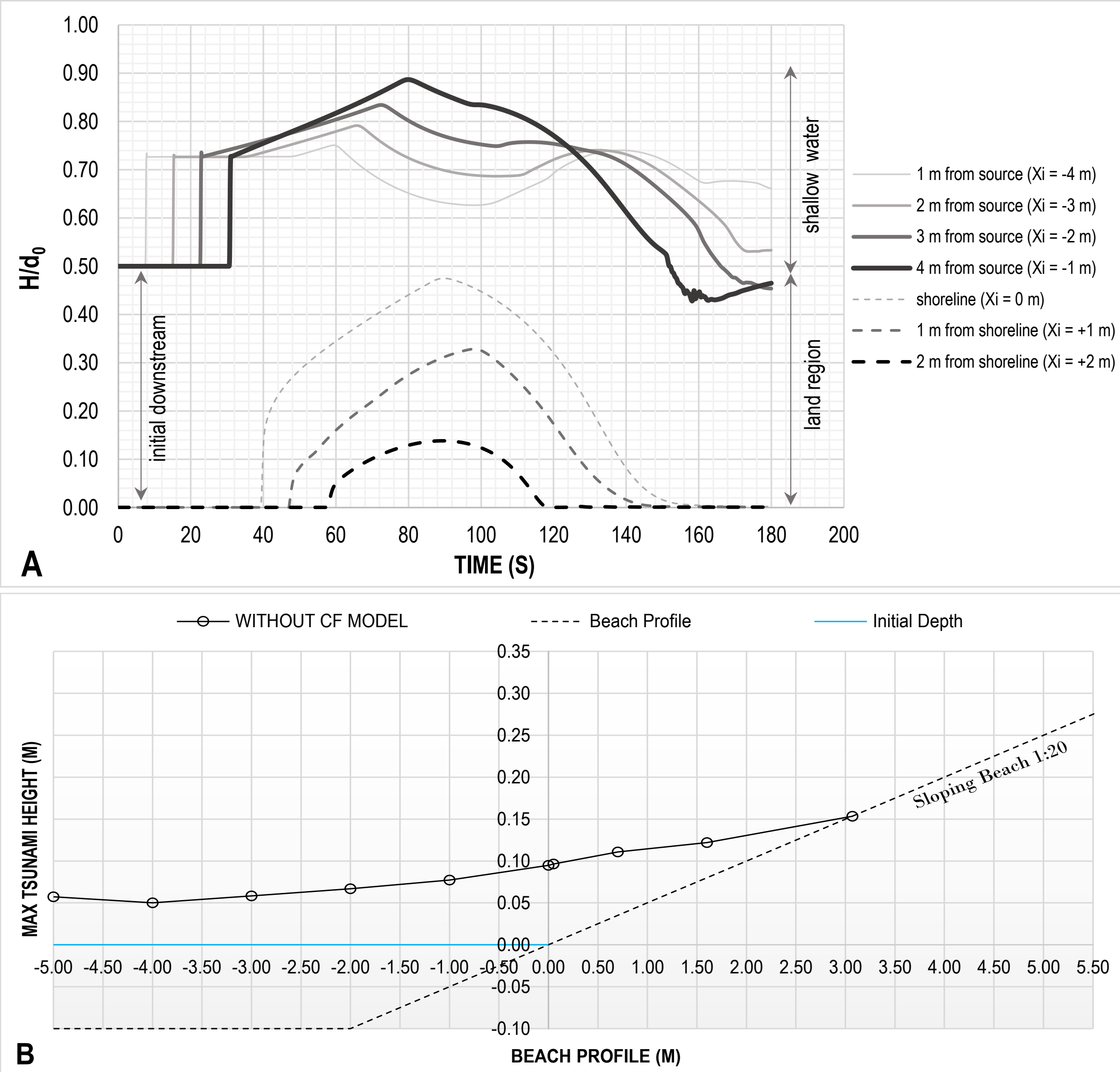


Figure 7. (A) The tsunami heights measured at various positions as a function of time and (B) the maximum tsunami height along the flume.

The performance of the methods related to the maximum run-up was tested using a variety of the reservoir depth, d_0. Figure 8 shows the corelation between the dimensionless tsunami height (H/d) and the dimensionless run-up height (R/d), where d = 0.05 m is the undisturb water depth at one meter distance from the shoreline model. The results match with Eq. (1), for H/d > 0.4. This range of H/d is used for further experiment.

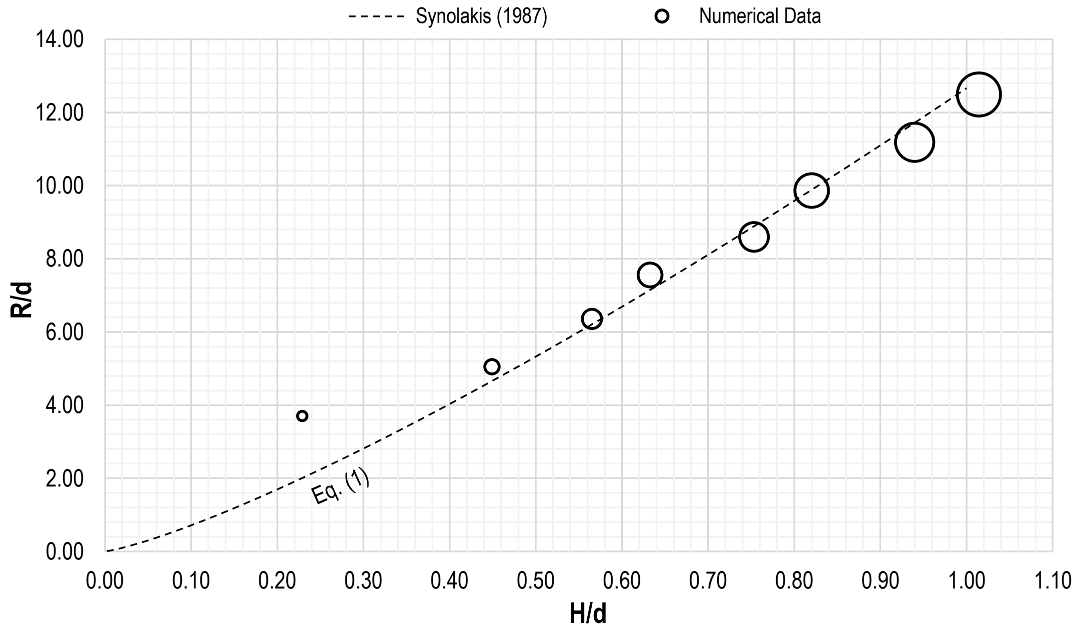


Figure 8. The relation between non-dimensional parameter R/d and H/d together with the run-up law (Eq. 1). Higher d_0 is indicated by larger symbol

4.2. The Effect of Coastal Forest on Tsunami Run-up

Forests of uniform and zigzag layouts (plantation patterns) of different densities were used to study the performance of CRM and ERM methods. The results of both methods are given in Figure 9. It is indicated in the figure that the tsunami run-ups of these models were significantly different. The ERM method produced lower run-up and hence less inundation than the CRM method. The land inundation was affected by the gap size between the trees where the smaller gap size yields lower run-up as expected. Besides that, the difference of the layouts also gives a significant effect on run-up height. Using the ERM method, the uniform layout produced higher run-up than the zigzag layout as can be seen in the figure (blue symbol). The CRM method, on the other hand, produced almost the same run-up value irrespective of the forest layout as can be seen in Figure 9.

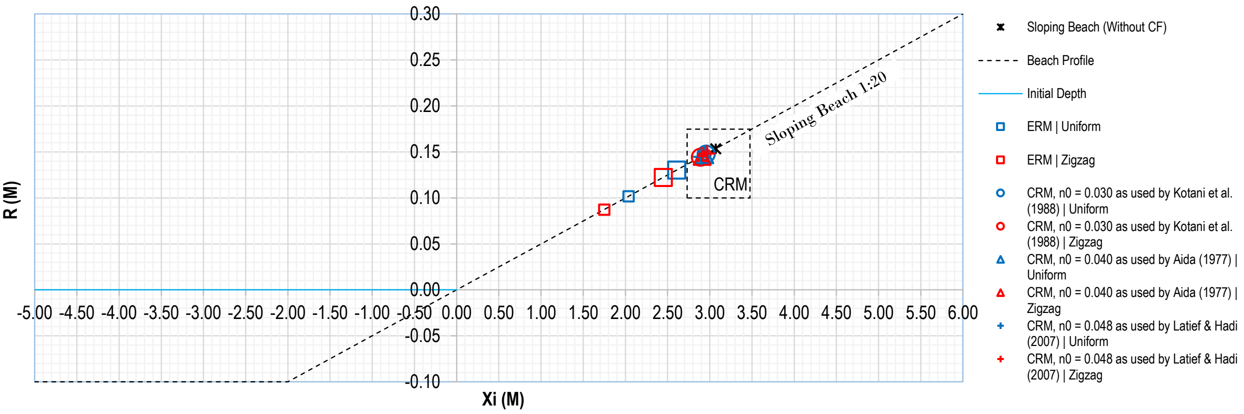


Figure 9. The run-up heights of CRM and ERM methods. Higher G is indicated by larger symbol

Theoretically, the zigzag layout may block the entire run-up path of the tsunami when there is no gap between each row of the trees. Hence, all the tsunami energy will be reflected back to the sea and no further run-up should exist behind the trees. As the gap between each row increases, the run-up behind the trees existed but at a reduced quantity. It may be concluded that in this case, the ERM is better than the CRM method in term of sensitivity against forest layout. The CRM method produced higher run-up than the ERM method for all variations of the model.

4.3. The Performance of the Alternative Method

The alternative model was tested to simulate tsunami propagation through a hypothetical coastal forest of 0.50 m long (along with the flume) and 0.60 m wide (across the flume). The tree's diameter was 0.02 m whilst the gaps were 0.02 m and 0.04 m. These models represented very dense forests which probably rarely happen. The selection of such densities was to make a clear comparison between the performances of the methods. The snapshots of the model simulation where the gap size was 0.02 m at zigzag layout are illustrated in Figure 10.

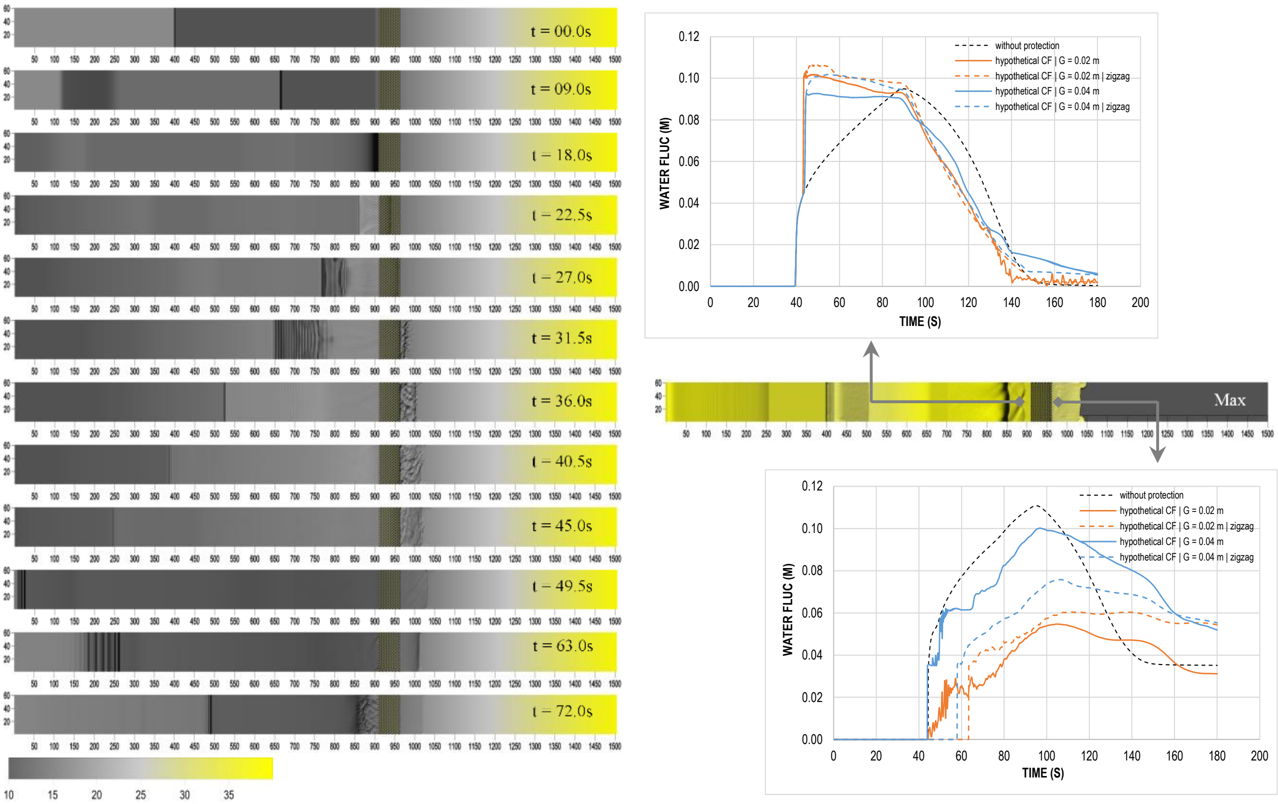


Figure 10. Snapshots of tsunami propagation along the numerical domain (left) and the water fluctuations at the upstream and the downstream of the model (right) for the case of zigzag layout with G = 0.02 m

The right side of Figure 10 shows that the water surface reduced over the distance of inundation incursion. Note that the water level increased in front of the forest model due to the reflection by the forest. The scale of the reflection and hence the backwater depends on the gap size and the model arrangement. It may be said that the velocity of the water at the upstream of the model decreased.

4.3.1. The Effect of Forest Layout against Tsunami Reduction

Figure 11 shows the tsunami water level at the maximum run-up at different layout (planting pattern) of coastal forests. In order to examine the effect of the layout, two different layouts were tested i.e. uniform and zigzag at constant gap size. The zigzag layout yields lower tsunami run-ups than the uniform layout. The reflection due to the trees plays more important role than the friction between the water and the surface trunk of the tree. Moreover, as the tsunami inundation decreased at the downstream of coastal forest, both the velocity and the energy reduced.

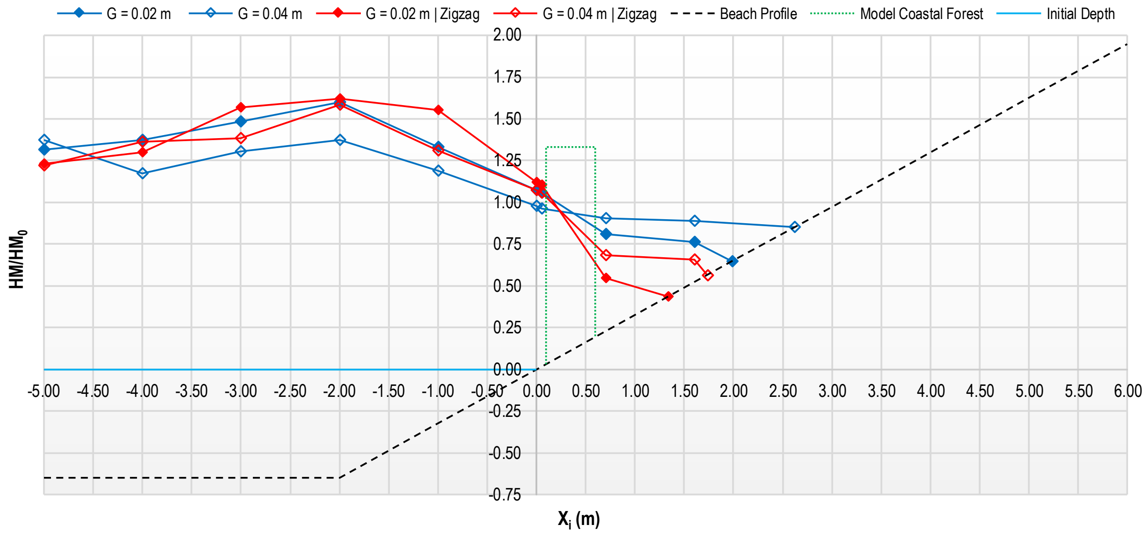


Figure 11. Distribution of maximum tsunami height near the coastline

4.3.2. The Effect of Forest Density against Tsunami Height

In order to examine the effectiveness of the forest density in reducing tsunami run-up, a dimensionless parameter HM_{do}/HM_0 that represents the ratio between the maximum tsunami height with and without forest model, are shown in Figure 12. In this case HM_{do}/HM_0 was measured at 0.10 m downstream of the forest model. In Figure 12, V_c/V represents the area of the trees relative to the total area of the forest. As V_c/V increases, HM_{do}/HM_0 decreases. This means that the higher is the forest density the more effective is the forest in reducing tsunami as expected. The effectiveness of the forest density increases more significantly for zigzag layout at high value of V_c/V.

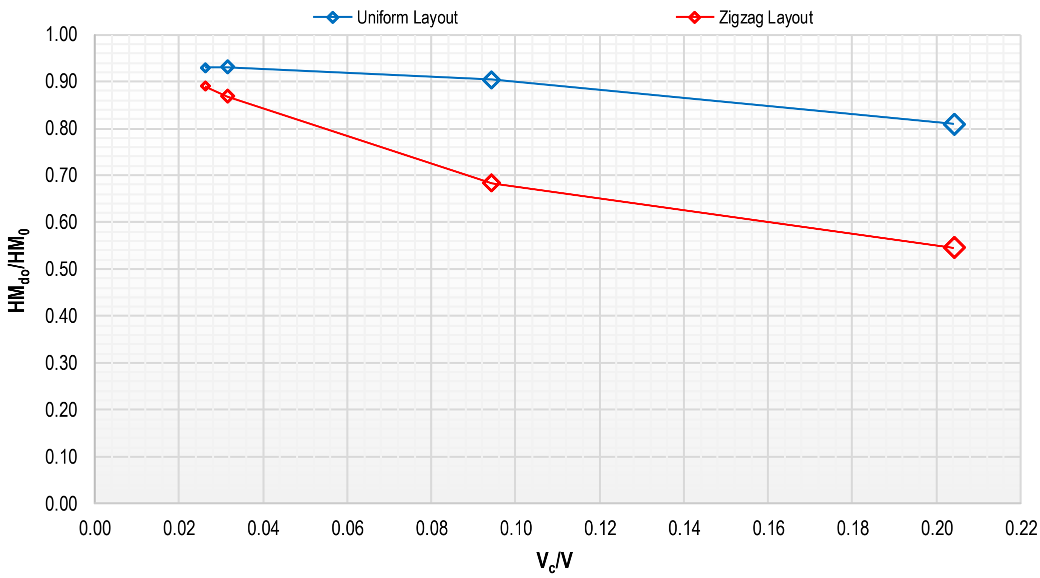


Figure 12. The effect of density variation over the maximum tsunami height behind the forest model. The higher density is indicated by larger symbol

4.3.3. Run-up and Inundation

The alternative method is in good agreement with the ERM method, especially for uniform layout as shown in Figure 13. The figure shows that the smaller gap size (larger forest density) produced lower run-up where more wave energy is reflected back to the sea. The alternative method resulted in lower run-up than the ERM method for the case of the zigzag layout. With the alternative method, the reflections of wave energy due to the trees were simulated better without modifying the roughness. It seems that the effect of reflection was larger than the change of roughness as simulated using ERM method as described further below.

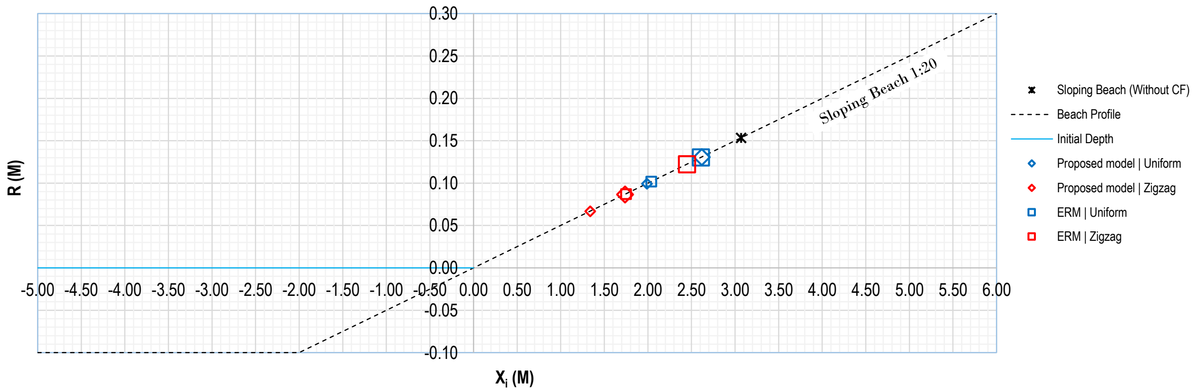


Figure 13. Tsunami run-up simulated using the alternative method and ERM method. The higher G value is indicated by larger symbol

The ERM method and the proposed method were further tested for highly dense hypothetical forest of zigzag layout. These were Case 1, Case 2, and Case 3 with 33%, 45.4%, and 50% of forest densities respectively as can be seen in Figure 14. The 50% density of forest model totally blocks the tsunami from propagating downstream as there is no space left for tsunami to flow through.

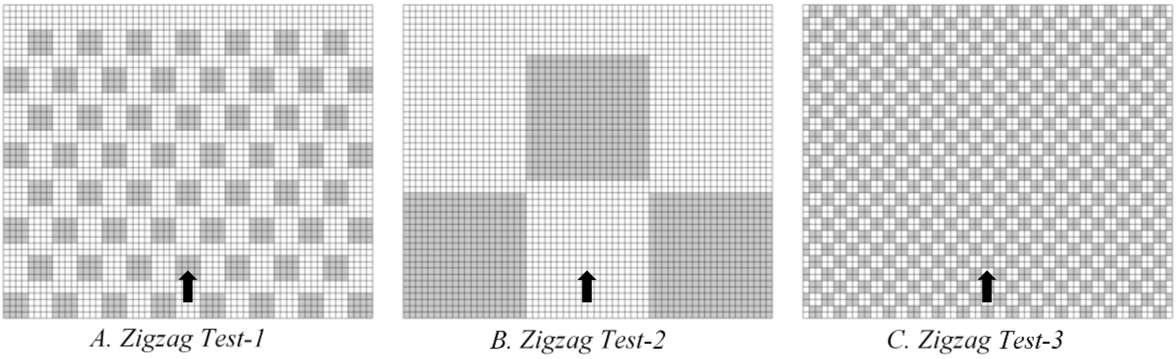


Figure 14. The layout of zigzag models. The arrows indicate the direction of tsunami

The result of the simulation using the ERM method indicated that the tsunami run-up through the forest of Case 1 was still relatively high as shown in Figure 15. Even with the hypothetical forest of 50% density and layout that totally blocked the space, the run-up was still relatively high. The alternative method yields more realistic result for 50% forest densities of the zigzag layout. Theoretically, such a forest represents a solid wall that is water tight. While the alternative method reflects the entire tsunami back to the sea (no run-up), the ERM method allowed for tsunami to flow through the forest and even run-up on the beach. Hence, it may be said that the alternative method performs better than both CRM and ERM methods. The drawback of the alternative method, however, is clearly the much longer computational time as smaller grids should be employed for the computation. The ERM method can be used in much larger cell grids since it requires only the bottom roughness of land use information, and the percentage of forest occupancy (see Muhari et al. (2011)).

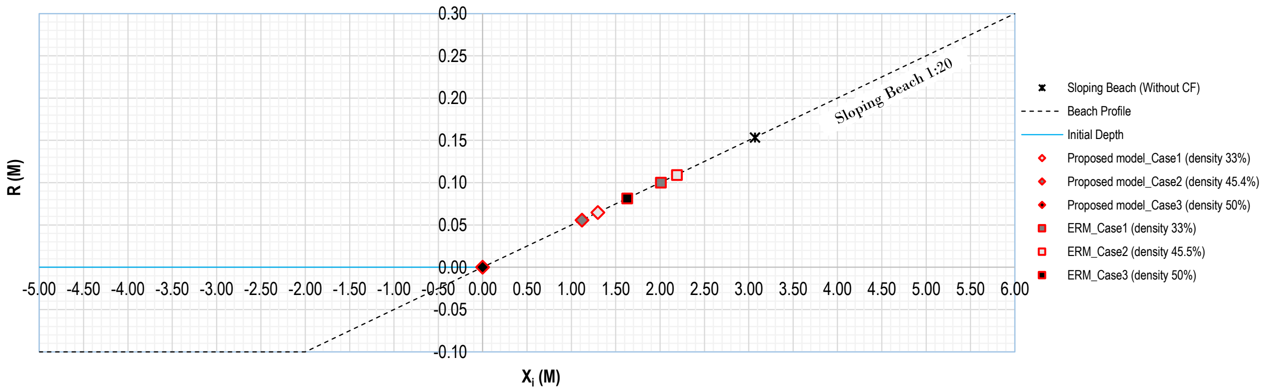


Figure 15. The relation of run-up against inundation for the zigzag case with different density

4.4. The Influence of Grid Size in Tsunami Simulation including Coastal Forest

Realizing the importance of certain variables namely gap size (G), grid size (Δx), tree diameter (D), run-up with coastal forest (R), and run-up without forest model (R_0), a dimensional analysis was performed to group the variables into dimensionless parameters as can be seen in Figure 16. Based on the figure, it may be concluded that the performance of the alternative method depends on the ratio of grid size and the model size. A smaller grid size produces better result. However, Figure 16 indicates that the difference between run-up was less than 3% even after refinement of $\Delta x^2/DG$ from 1.0 to 0.01 where $\Delta x \leq D$.

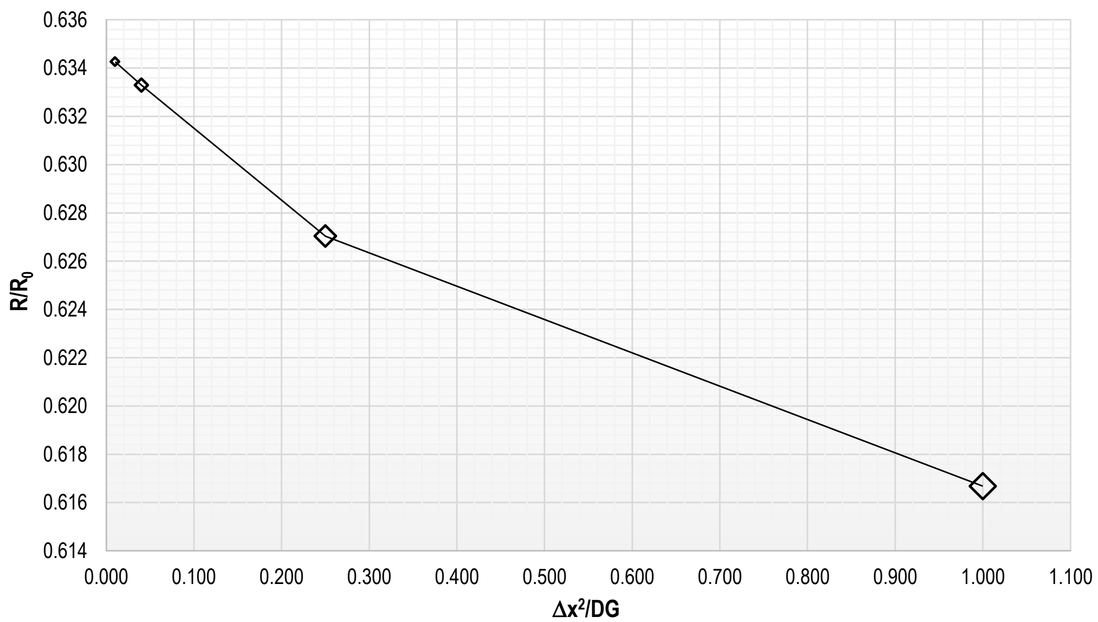


Figure 16. Correlation between the grid sizes in generating tsunami run-up based on the alternative method. The larger Δx is indicated by larger symbol

5. CONCLUSION AND RECOMMENDATION

The ERM method is better than the CRM method where the ERM somehow accommodates for different types of forest layout. The alternative method is more accurate than both the CRM and ERM methods when simulating tsunami run-up through the highly dense coastal forest. Even with moderately high density (11%), the difference between the alternative method and the ERM is significant, where the alternative method produced lower tsunami run-up. At much lower density, however, the ERM and the proposed method are expected to produce a very similar result. The alternative method is more time to consume, however, with the advancement of technology, it is hoped that in the future such alternative method will be more applicable. For relatively low forest density the ERM method is recommended.

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