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SIMPLIFIED DEBRIS FORCE DUE TO TSUNAMI ON A RECTANGULAR COLUMN

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ABSTRACT

Tsunami force on structures can be devastating depending on the size of the tsunami surge and the strength of the structures. In addition to hydrodynamic force, debris force either single debris or in group may hit a building at smaller area and hence resulting in greater pressure impact. Such impact may be of significant if applied on columns of buildings. The type, size, characteristics and approached angles of debris vary considerably. It is important to understand the characteristics of debris flows under tsunami surge and their impact on structures based on simplified debris of basic shapes. Physical model simulations were carried out using a flume of 20.80 m long, 0.6 cm wide and 0.45 high. The flume was divided in to two parts using a gate that can be opened quickly. The upstream part was used as a basin to store water to a certain depth. When the gate was opened, the water in the basin surged downstream similar to tsunami surge on land and hit a column where a load cell was installed to measure the pressure. The speed of the surge was recorded based on the arrival time of the surge front at a number of stations. The surge height was varied by varying the basin depth. Debris of various sizes under similar tsunami surges were then placed in front of the column at various distances. The tsunami surge and debris speed as well as the debris force on the columns were measured and compared with clear water tsunami force. The results indicate that the debris velocity is slower than the front surge depending on the bed friction, ρ and the degree of immersion. Although the debris hit the column at slower speed, its impact force is higher than the hydrodynamic force. Since debris requires time to gain speed as they are dragged by the surge, the distance between the columns and the initial location of the debris is an important parameter. The theoretical approach of debris (sphere) force on a rectangular column was shown to be comparable to the experimental results.

Keywords: Tsunami, Force, Debris, Simulation

1. INTRODUCTION

During a tsunami attack, a lot of civil engineering structures, trees, cars, and other objects along the way of the tsunami surge may be demolished, rooted up and drifted by tsunami propagation. These material or debris, give additional impact to structures along the course of the debris.

Tsunami force on buildings is devastating to normal buildings. The force varies with tsunami surge speed on land, the size of both tsunami and the structures, and the effect of surrounding environment. A lot of researches have been carried out to uncover many possible scenarios of tsunami force on structures. In addition to fluid force, the impact of debris on building during tsunami attack may be of significant. Fukuyama et al (2013) mentioned that most of the non structural parts of the buildings attacked by the tsunami 3-11 in Japan were damage. They noted that although significant failure of structural frame due to debris impact was not observed, a multi-story wall of an apartment was damage probably by the debris impact.

Although tsunami surge velocity may somehow reduce due to extra energy loss to drift the debris, the impact of the debris may result in more severe destruction. First, the impact of solid debris also depends on the size of the debris. The larger is the debris, the greater is the impact. Secondly, the impact may focus on a small area of the structure or building. Therefore, a study on the probability of maximum force due to debris during tsunami attack is important.

Small debris such as stones and gravels bring different impact to structures when compare with large debris such as trucks and containers.

In addition to the direct impact of debris to buildings, debris that are trapped between columns of buildings may resulted in additional force that have to be hold up by the column. This damming condition should also be considered. During tsunami disaster in Aceh in 2004, mosques normally survived from the hazard. This is due to the relatively better construction of the mosques and the fact that mosques are normally built with minimum walls. When damming occurs, tsunami force on the debris is transferred to the columns which resulted in significantly larger force.

2. THEORETICAL CONSIDERATION

A number of theories on tsunami force have been proposed where most of them concern with clear water tsunami force on buildings either solid or with openings, with or without protection, cylindrical shape and rectangular shape structures at different positions relative to the shore line. Clear water tsunami force on solid buildings depends largely on surge Froude number, relative height of the building to the surge and the width of the building. Such force may drag and demolish the buildings completely. Higher percentage of openings on buildings may reduce the force on buildings (Triatmadja and Nurhasanah, 2012). Similarly, Triatmadja and Nurhasanah (2011) showed that elevated buildings suffer less tsunami force.

The situation can be completely different when debris hit the buildings. Intuitively, as debris is solid and heavier than the water, the surge has to use its energy to drag the debris which causes reduce surge velocity. However the sudden changes of momentums of the debris due to the impact with structures or buildings exert force that may be larger than the clear water tsunami force.

Following USAEWES-CERC (2001) surge force on a wall per unit length can be written as

$$F = 4.5\rho g h^2 \quad [1]$$

where h is the inundation depth. The equation can be derived using impact force on a building

$$F = C_f \rho b h U^2 \quad [2]$$

Letting the surge Froude number (F_r) = $U/\sqrt{gh}$ =2, it is found that C_f = 1.11. In fact Triatmadja and Nurhasanah found that C_f ranging from 0.6 (for overtopping building) to 1.03 for non overtopping rectangular column. Eq. [2] may be written as

$$F = 1.1\, \rho A U^2 \quad [3]$$

Debris force on structure in air may be explained in three different approaches (Naito et al, 2010) namely Constant stiffness, Impulse momentum, and Work energy approaches.

The maximum force based on

a) Constant stiffness

$$F_{max} = u\sqrt{kM} \quad [4]$$

where u is the speed, k is the stiffness and M is mass.

b) Work-energy approach relate

$$F_{max} = \frac{u^2 M}{2\Delta x} \quad [5]$$

where Δx is the distance or the strain resulted from the impact. The maximum force of

c) Impulse momentum is

$$F_{max} = \frac{\pi}{2}\frac{um}{\Delta t} \quad [6]$$

where m is the mass of the debris. The first two approaches are actually the same in term of requiring data of stiffness of both the debris and the structures. The third approach requires only the time required to stop the debris.

Ko (2013) conducted simulations of the impact force of container models drifted by tsunami on a load cell which was installed on a vertical column. The container models were 1.22 m (long) x 0.52 m (high) x 0.49 m (wide) made of aluminum and acrylic. The Δt (time of impact) were shown to depend on whether the debris force in the water or in the air, and also depend on the stiffness of the material. The average impact time of aluminum debris in the water was approximately 1.1 ms, whilst the average impact time of an acrylic debris was 2.25 ms.

In reality, the situation may be different. First the debris is drifted freely by water which makes the angle of approach uncontrolled and can be from many directions not necessarily parallel to the flow. Hence the maximum flow can only be attained when the debris hit the structure at the most severe angle. Secondly there is an added mass of water that pushes behind the debris. Third, the speed of the debris is not the same as the speed of the flow. This is because large debris may not be fully buoyant and hence the bottom friction play an important role.

Accommodating for uncertainties during the impact, Eq. [6] may be written simply as

$$F_{max} = \alpha \frac{u\, m}{\Delta t} \quad [7]$$

where α is the coefficient of force due to uncertainties and force distribution with time. Assuming that the debris is totally submerged and with the velocity equals the fluid, $m/\Delta t = uA\rho$ where A is the area of the structure. Eq. [7] may be written as

$$F_{max} = \alpha A \rho u^2 \quad [8]$$

Eq. [8] has been used in the field of terrain land slide and debris flow by many such as Watanabe & Ikeya (1981) where α was assumed to be 2.0. VanDine (1996) indicated that α varies from 1.5 to 2 but a single boulder impact should be calculated using Hertz contact force equation. Geotechnical Engineering Office (2000) recommended the use of α equals 3 for the debris barriers structures. Ishikawa et al. (2008) found that the peak load of pumice stones debris was nearly twice the design load (Eq. [8] with α = 1) or suggests that α is nearly equals 2.

It was shown by Lukkunaprasit (2009) that the maximum hydrodynamic force on a box was not during the maximum surge speed. Such maximum surge speed occurs with smaller surge depth and resulted in a non maximum force. As the speed slowed down and the surge height increases slightly behind the surge front, the force increases up to the maximum force.

The drag force on a sliding debris may be expressed as

$$F = \frac{1}{2}\rho C_d A (U-u)^2 - fW_b \quad [9]$$

where U is the fluid velocity and u is the debris velocity, f is the friction coefficient between the debris and the ground and W_b is the weight of the debris in the water. As the debris gain speed, the velocity of the debris (u) should be smaller than the surge velocity (U) to balance the friction when F = 0. In our case, the friction is small and hence u should be finally close to U.

Letting F = 0 at the equilibrium condition, we have

$$u = U - \sqrt{\frac{2fW_b}{\rho C_d A}} \quad [10]$$

Before reaching the equilibrium condition, the debris velocity increases with acceleration depending on the debris material and the velocities of both the surge and the debris. Assuming that the debris is completely submerged and ρ_s (density of the debris) is greater than ρ (density of water), the acceleration of sliding debris may be calculated based on Eq. [11].

$$\frac{du}{dt} = \frac{\rho C_d A (U-u)^2 - 2 f W_b}{2 \rho_s V_s} \quad [11]$$

For a sphere moving on a flat surface due to a surge, the acceleration may be written as in Eq. [12].

$$du = \left(\frac{3}{4} C_d \frac{\rho}{\rho_s} \frac{(U-u)^2}{D} - \frac{f g (\rho_s - \rho)}{\rho_s}\right) dt \quad [12]$$

The progress of the debris velocity may be calculated by integrating Eq. [12].

Carty (1957) studied the value of C_d on a rolling sphere that fully immersed on an inclined bed. The C_d is approximately equal to 1.0 for R_e between 10^3 and 10^4 and drop significantly for $R_e > 10^4$. C_d is approximately equals 0.5 at R_e equals 5.10^4. In our study, based on the surge front velocity and the ball diameter, R_e ranged from 4.4 10^4 to 7.8 10^4. The relative R_e changed with time as the debris' speed increased. For a rolling sphere the friction coefficient is

$$f = \frac{2}{5g} \frac{du}{dt} \quad [13]$$

For a fully submerged sphere the drag force may be written as

$$du = \frac{3}{4}\left(C_d \frac{\rho}{\rho_s} \frac{(U-u)^2}{D}\right) dt \quad [14]$$

Based on Eq. [9] the net force on the submerged sphere rolling on a flat surface may be written as

$$\rho_s \frac{du}{dt} = \frac{3}{4} \rho \left(C_d \frac{(U-u)^2}{D}\right) - \frac{2}{5} (\rho_s - \rho) \frac{du}{dt} \quad [15]$$

After some algebra yields

$$u = \int \frac{15}{4} \frac{\rho}{(7\rho_s - 2\rho)} \left(C_d \frac{(U-u)^2}{D}\right) dt \quad [16]$$

Eq. [16] is valid when $u < U$.

3. EXPERIMENTS

The experiment was carried out in the Hydraulics and Hydrology Laboratory, Research Center for Engineering Science, Universitas Gadjah Mada using a small flume measuring 20.80 m long, 60 cm wide and 45 cm deep. The flume was facilitated with a quick released gate that capable of generating a dam break surge to simulate tsunami surge on land. The water depth in the basin (upstream part of the flume) was varied from 10 cm to 40 cm to vary the surge speed and height. The debris was represented by marbles, and concrete balls of different size and density. A hollow rectangular column of 5.4 cm by 6.0 cm was located about 4.76 m downstream of the gate. The column was fixed at both ends. The front surface of the column from the bottom to 4 cm above the bottom was replaced by a plate of 5.4 cm by 4 cm that was used as force sensor. The debris is expected to hit this area where the force may be measured using pre calibrated load cell. From the recorded time story from the load cell, the duration of impact may be determined. In order to assure that the debris hit the column, a guide rail using a pair of angle steel of 2 cm x 2 cm x 2 mm thick starting from 1 m downstream of the gate to 12 cm in front of the column. This was to provide for the debris to exit from the rail after hitting the column. The distance between the angle steels was 7 cm. The guide rail was relatively small so that its effect on debris velocity and subsequently the force on the column was expected to be insignificant.

The layout of the experiment is shown in Figure 1 and Figure 2.

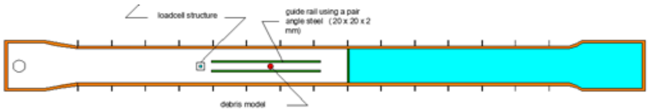

Figure 1. Experimental Layout

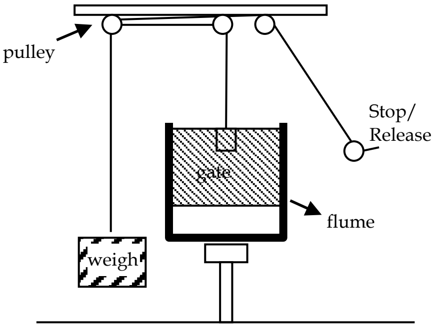

Figure 2. Quick release gate scheme

The variation used in the experiment is given in Table 1.

Table 1. Variations used in the experiment

Basin depth (m)	Debris	Distance of the debris to the column (m)
0.30, 0.20, 0.10	D =0.044 m, ρ=2.10	0.01, 0.10, 0.20, 1.0, 2.0, 3.8
0.30, 0.20, 0.10	D =0.044 m, ρ=2.91	0.01, 0.10, 0.20, 1.0, 2.0, 3.8

4. RESULTS AND DISCUSSION

4.1 Surge velocities.

The surge velocities depend on basin depth or the surge height as expected. The measured surge velocities are given in Figure 3.

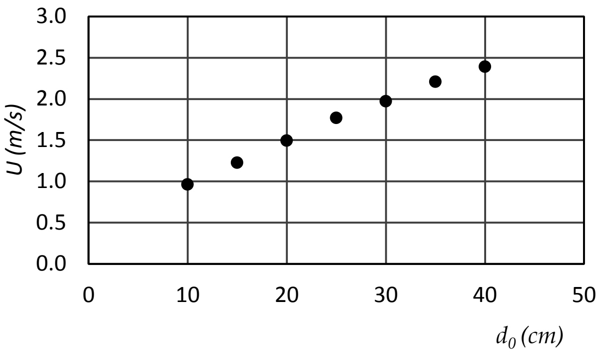

Figure 3. Surge speeds as a function of basin depth

4.2 Debris velocities

It was observed that the front of the surge moves faster and left the debris behind. As the debris got the momentum the speed was almost the same as the surge. Examples of the debris velocities are given in Figure 4 and Figure 5. Both figures indicate that the surge velocities are faster than the debris. It is also indicated that the debris velocities are increasing as the debris travel further away downstream. The speed of the debris was measured as the average speed after travelling a certain distance from its original position to the location of the rectangular column. It can be seen that during the 0.10 m and 0.20 m the speed of the debris were significantly slower than the surge front. After travelling 1.0 m, or approximately 23 times of debris diameter, the debris velocity becomes closer to the surge velocity. From there on, the debris velocity only marginally increase in speed. This indicates that the force exerted by the surge front was equal to the friction force exerted by the bed of the flume. The surge force to maintain the debris velocity at its maximum speed is slightly higher for higher ρ_s. This is indicated by the difference between the surge velocities and the debris velocities in Figure 4 and Figure 5.

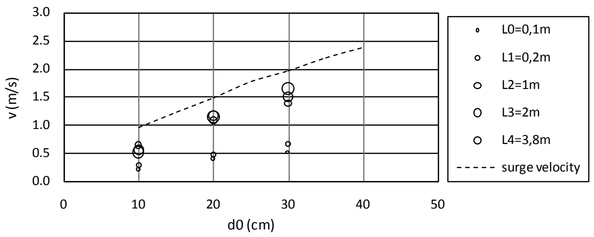

Figure 4. Average debris velocity for *D* =0.044 m, ρ =2.10 ton/m^3 measured after travelling a distance *L* as indicated in the figure.

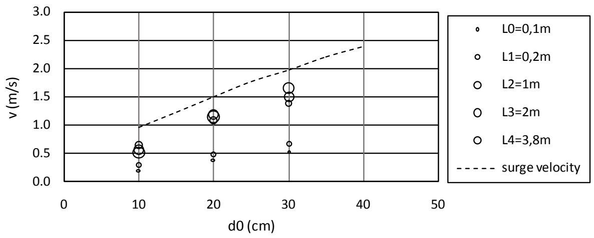

Figure 5. Average debris velocity for *D* =0.044 m, ρ =2.91 ton/m^3 measured after travelling a distance *L* as indicated in the figure.

The relative debris velocities are given in Figure 6.

The theoretical predictions based on Eq. [16] were drawn together with the average debris velocity data in Figure 6 by assuming the drag force and the value of friction coefficient. The drag force coefficient has been assumed to follow Carty's study whilst the friction coefficient was assumed based on purely rolling ball on a flat surface. Based on Figure 6 it may be said that the debris velocity were significantly slower than the surge front speed. Eq. [16] predicts quite closely the debris velocity when the surge is significantly higher than the debris diameter. It overestimates the debris velocities as the surge height become closer or slightly less than the debris diameter.

Figure 6 also indicates that the debris was not purely rolling as they were slower than the predicted value by Eq. [16]. Therefore a different friction coefficient *f* was assumed and the debris velocities based on Eq. [12] were compared with the data in Figure 7. Figure 7 indicates that the debris velocities are better represented by Eq. [12] with an appropriate friction coefficient *f*. For very shallow surge where the debris was not fully immersed as in the case of *d* = 0.10 m, Eq. [12] over estimates the experiment. One of the reason is that Eq. [12] assumes that the debris was fully immersed that resulted in an over estimated drag area and reduces the effect of friction. It is interesting to note that for *d* = 0.1 m, *u/U* reached a maximum at certain *L/h* and then decreased with increasing *L/h*. Since the debris moves much slower than the front, it was left significantly behind and was on the position where the velocity was significantly slower than the front as indicated by Lukkunaprasit (2009). We have used the average front velocity as a constant in Eq. [12] and [16] and hence could not simulate the decreasing debris velocity.

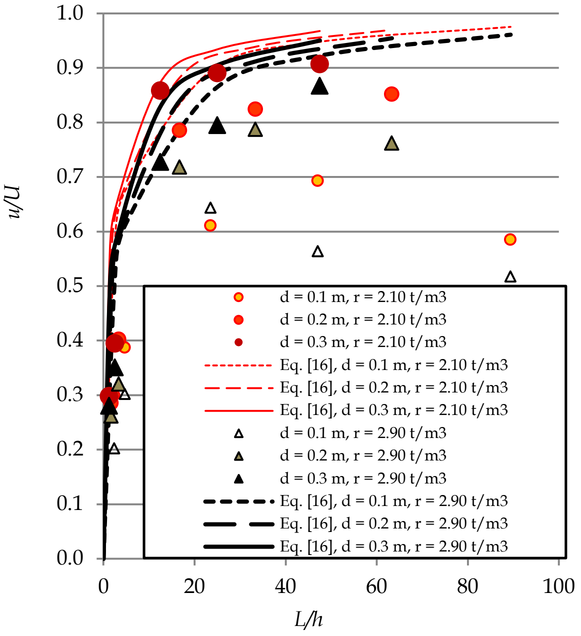

Figure. 6. Relative debris velocity vs relative distance of travel (r = ρ of debris)

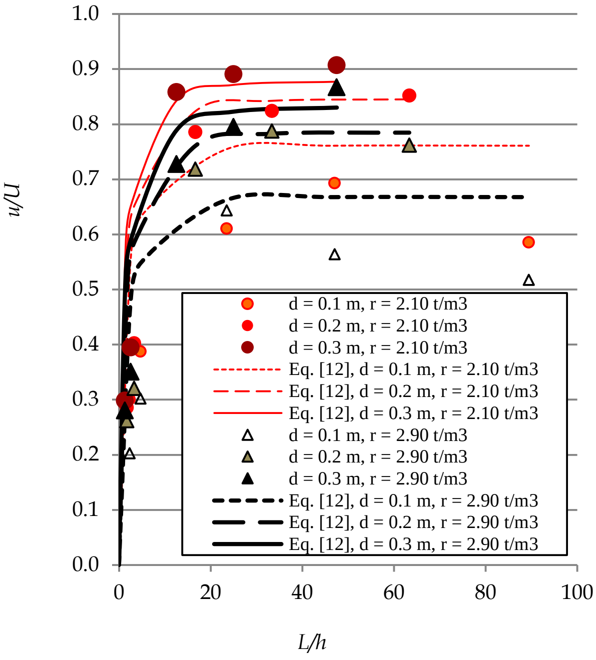

Figure 7. Relative debris velocity (based on Eq. 12) vs relative distance of travel (r = ρ of debris)

4.3 Duration of debris impact on the rectangular column

The duration of impact depends on the debris velocity. The higher is the debris velocity, the longer is the impact duration. Figure 8 shows an example of impact duration of debris. The duration of impact has been assumed equals approximately a half of the force duration. The declining force occurred when the debris has stopped completely and hence was not considered as the impact duration. Figure 9 shows the variation of impact duration as a function of initial debris distance to the rectangular column. The debris with relatively larger ρ (shown by filled circle in Figure 9) seems to have a marginally longer duration of impact since their momentum were higher during the impact.

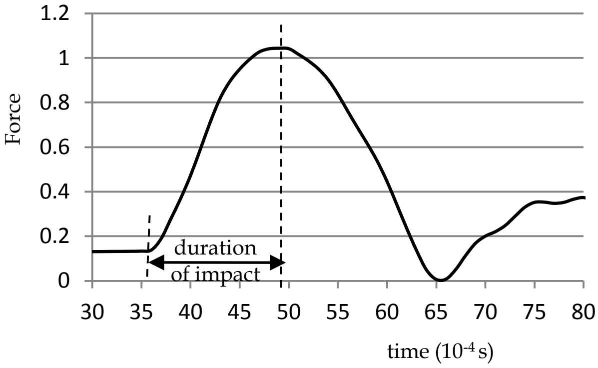

Figure 8. Example of recorded force time history

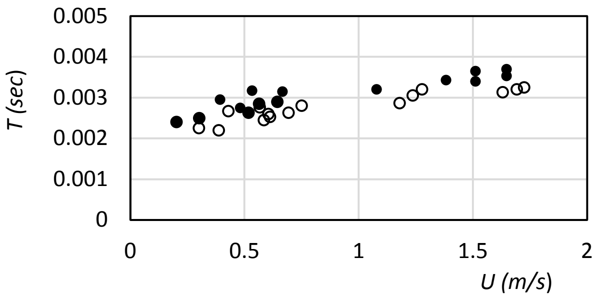

Figure 9. Duration of debris impact on rectangular column. (filled circle ρ = 2.9 t/m³, hollow circle ρ = 2.1 t/m3)

4.4 Debris force on a rectangular column

The debris forces on the column are presented in Figure 10 and Figure 11. Eq. [8] is used to predict the maximum force on the rectangular column. Assuming that the force was distributed following a sinusoidal function with time, the maximum force is therefore may be written as in Eq [6]. Eq. [6] has been used by Naito et al (2008).

Using the measured data (u and Δt), Eq. [6] may be drawn together with measured force as shown in Figure 10 and Figure 11. The agreement between the measured data and Eq. [6] is satisfactory indicating that the measurement of u, and Δt were quite accurate.

Unlike in Figure 10 and Figure 11, Figure 12 was constructed using Eq. [6] for debris force prediction and Eq. [12] for debris velocity. As can be seen the agreement between the measured force and the predicted force in Figure 12 is not as satisfactory as in Figure 10 and Figure 11. The discrepancy was due to inaccurate prediction of debris velocity as shown in Figure 7.

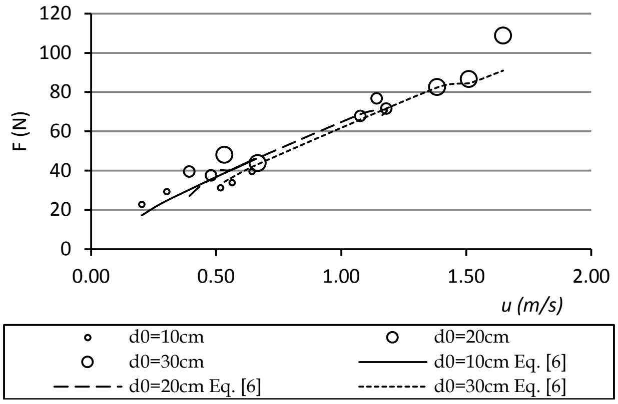

Figure 10. Debris (sphere ρ = 2.9) force on a rectangular column based on Eq. [6] where u was based on measurement.

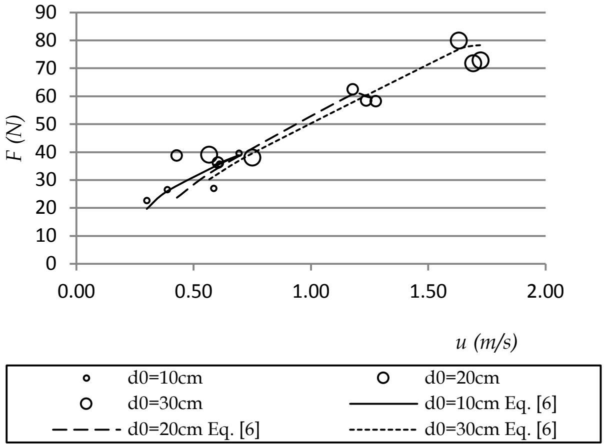

Figure. 11. Debris (sphere ρ = 2.1) force on a rectangular column based on Eq. [6] where u was based on measurement.

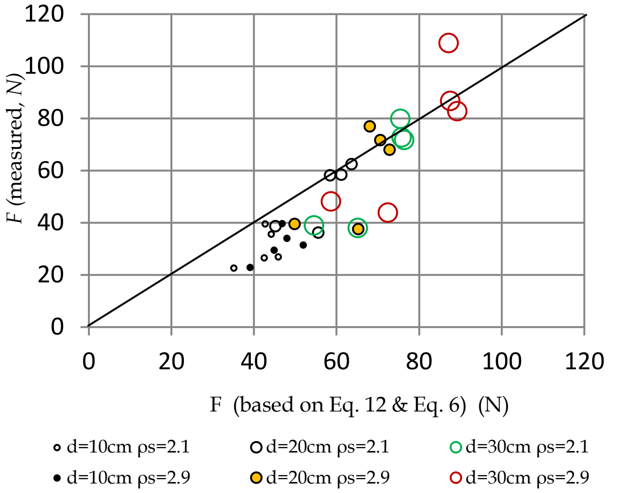

Figure. 12. Debris (sphere) force on a rectangular column. The theoretical approach was based on Eq. [6], where u was calculated based on Eq. [12].

The clear water tsunami force on the rectangular column may be calculated using Eq. [3]. Using the experimental data for d = 30 cm leading to approximately surge height h = 0.08 m and U = 2.0 m/s and for b =0.054 m, the maximum total force on the column equals 19 N. This is approximately 25% of the maximum debris (sphere, ρ = 2.1, D/h = 0.55) force on the column. Such example indicates that the debris force on a column can be more dangerous than the hydrodynamic impact.

5. CONCLUSIONS

1. A simplified debris model of sphere has been carried out to understand the characteristics of debris force on rectangular column. It is shown that the velocity of the debris may be calculated using Eq. [12]. The equation produce accurate debris velocity when the debris is completely submerged otherwise it may produce significantly less velocity than the surge front depending on *f*. After a certain distance when the position of the debris was significantly behind the front the discrepancy tends to increase.
2. The debris force can be predicted using Eq. [6] when u and Δt are known. The debris force is much higher than the hydrodynamic force of the surge.
3. The debris force on a rectangular column that is based on Eq.[6] and Eq. [12] is comparable to the experiment especially when the debris was completely immersed.
4. More suitable equation is required to improve the debris force prediction by accommodating (a) the slowing down of the surge velocity behind the surge front and (b) the drag force and friction coefficients of the debris that is not completely submerged.

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