**ENERGY LOSS IN A FLOW THROUGH VEGETATION OF VERTICALLY TWO DIFFERENT LAYERS**

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## 1. INTRODUCTION

Tsunami is known as a terrifying disaster and large tsunami can cause massive damage to the coastal areas. When the tsunami reaches the shore area, it runs up toward the land with increasing height (Tanaka et al., 2013). The Indian Ocean tsunami that occurred on December 26$^{th,}$ 2004 and had a magnitude of 9.3 damaged 14 countries affecting Indonesia greatly. Fig. 1 shows the situation of area near Aceh Province, Indonesia before (left) and after (right) 2004 tsunami. Extensive damage to infrastructure can be seen due to combined effect of tsunami currents and floating debris.


Fig.1 Aceh Province, Indonesia before and after the 2004 Indian Ocean tsunami (images taken from Google Earth).

For tsunami mitigation, vegetation system is considered as one of the effective solution (Tanaka et al., 2011). Several previous studies (Tanaka et al., 2011) have discussed the effects of vegetation in mitigating tsunami. Intensive numerical simulations were also conducted and the effect of vegetation was quantitatively evaluated under many different tsunami conditions (Nandasena et al., 2008). Recently, Pasha and Tanaka (2016) conducted laboratory experiments to clarify the energy loss through vegetation not only by drag force but also by the downstream flow pattern change and confirmed increase in energy reduction with increasing vegetation density. The objective of this study is to further clarify the energy loss mechanism by compound defense system comprising of two different types of vegetation. This study will help to design multiple protective measures for tsunami mitigation in future.

## 2. EXPERIMENTAL SETUP AND CONDITION

### 2.1 Experimental Procedure and Flume Characteristics

Laboratory experiments for 9 different cases (Table 1) were conducted in a flume (constant bed slope 1/500) which is 5m in length, 0.7m in width, and 0.5m in height, in Saitama University. Tsunami flow is usually considered as unsteady and non-linear flow; hence the physical experiment is usually conducted using a flume with sudden opening gate or wave generator. However, it needs a large-scale facility to simulate the flow and measure energy loss. Since the tsunami duration is quite long and the flow can be considered as a steady flow except for the initial inundation therefore steady sub-critical conditions were prevailed in the experimental flume. In the current study, as a first step, the initial Froude number ($Fr_o$, where reference velocity and water depth are used without a vegetation model placed in a channel) was set around 0.55-0.75 representing steady flow conditions by changing water depths from 3 to 7cm with an increment of 0.5cm.

The vegetation model was mounted at 165 cm from the upstream inlet. The water level was measured with a rail mounted point gauge throughout the center of flume. The discharge was measured using a flow meter (Signet 8150 Flow Totalizer). Mean velocity was calculated by using discharge and water depth results. The water velocity calculated from flow meter discharge reading was compared with the depth averaged velocity calculated from particle image velocimetry (PIV) (Laser Light Sheet: G200, high speed digital CCD camera: K-II, fps: 600, flow analyzing software: FlowExpert2D2C, Katokoken Co., Ltd.). The difference was less than 5%. 2.2 Vegetation Conditions

To optimize the compound defense system for tsunami mitigation, two vertically different layers of vegetation with different density were selected for making the vegetation model. The layer-1 (lower layer) was considered as fast growing vegetation with a lower height of stem and smaller diameter (e.g. *Pandanus odoratissimus*) while layer-2 (upper layer) was selected as a slow growing vegetation (e.g. *Cocos nucifera*) (Fig. 2a).

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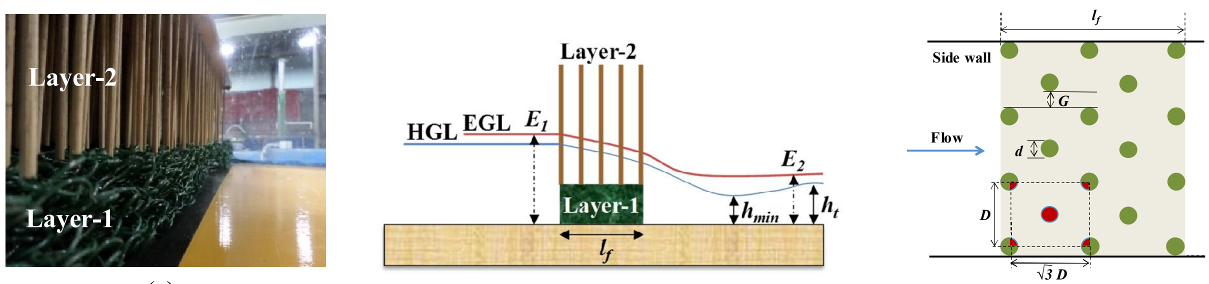
Table 1 Experimental conditions

| Case No. | $Fr_o$ | $G/d$ | $D$ (cm) | $l_f$ (cm) | $\theta$ (%) Layer-1 | $\theta$ (%) Layer-2 | $dn$ (No. cm) Layer-2 | Forest Type |
|---|---|---|---|---|---|---|---|---|
| 1 | | - | - | 8.23 | 65 | | - | Dense, Layer-1 only (L1-D) |
| 2 | | - | - | 23.60 | 65 | | - | Intermediate, Layer-1 only (L1-I) |
| 3 | | - | - | 52.48 | 65 | | - | Sparse, Layer-1 only (L1-S) |
| 4 | | 0.25 | 1 | 8.23 | - | 87 | 380 | Dense, Layer-2 only (L2-D) |
| 5 | 0.57-0.73 | 1.09 | 1.67 | 23.60 | - | 95 | 391 | Intermediate, Layer-2 only (L2-I) |
| 6 | | 2.13 | 2.5 | 52.48 | - | 98 | 388 | Sparse, Layer-2 only (L2-S) |
| 7 | | 0.25 | 1 | 8.23 | 65 | 87 | 380 | Dense, Layer 1 and 2 (CO-D) |
| 8 | | 1.09 | 1.67 | 23.60 | 65 | 95 | 391 | Intermediate, Layer 1 and 2 (CO-I) |
| 9 | | 2.13 | 2.5 | 52.48 | 65 | 98 | 388 | Sparse, Layer 1 and 2 (CO-S) |




(a) (b) (c)

Fig. 2 (a) Two-layers vegetation model, (b) flow structure scheme, (c) detailed arrangement of layer-2.

For a model scale of 1:100, the height of layer-1 of vegetation model was selected to be equal to 5 cm referring to the height of *Pandanus odoratissimus*. Plastic material with a constant porosity ($\theta$) of 65% was used to model the vegetation layer-1 for all the cases. Whereas, the trees of layer-2 were set in a staggered arrangement and modeled by wooden cylinders having diameter of 0.004m based on the physical scaling and the average diameter of *Cocos nucifera* (Orwa et al., 2009). Fig. 2 and Table 1 show the details of vegetation arrangement where, $Fr_o$ is initial Froude number, $G$ is the spacing between each cylinder in a cross-stream direction, $d$ is diameter of cylinder, $D$ is the distance between cylinders, $l_f$ is the width of vegetation model, $\theta$ is porosity of vegetation, $dn$ is vegetation thickness, L1 is layer-1 vegetation only, L2 is layer-2 vegetation only, CO is combination of layer-1 and layer-2 vegetation. D, I and S represents dense, intermediate and sparse vegetation, respectively. Although the porosity of layer-1 vegetation kept constant for all the cases, but its width was selected in accordance with the width of layer-2 vegetation against dense, intermediate and sparse vegetation arrangements. Thus, both the layers have same width in combined cases i.e., 7, 8 and 9 (Table 1) while, cases 1 to 3 are of layer-1 only and cases 4 to 6 are for layer 2 only. Referring to the study of Takemura and Tanaka (2007), flow structures are different depending upon $G/d$ arrangement of vegetation model. Spacing between trees ($D$) and forest width ($l_f$) were determined under same vegetation thickness ($dn$) which is defined as a product of the diameter of breast height of tree and number of trees in a rectangle with a frontage of unit length along shoreline and depth equal to diameter of tree ($d$), (Shuto, 1987) Fig. 2c. In this study $dn$ was calculated as:

$$dn = \frac{2}{\sqrt{3}D^2} l_f d \times 10^4 \tag{1}$$

Where $10^4$ in above equation adjust a unit in Shuto's definition of $dn$ because $D$ and $l_f$ are in cm, and $d$ (0.004) is in m. In this study $dn$ was set to around 380 in all experiments.

**2.3 Non-Dimensional Pi Groups**

Using Buckingham's Pi theorem, the following dimensionless groups were developed:

$$\Delta E = f\left(\mathrm{Re}, Fr_o, \frac{G}{d}, dn, \theta\right) \tag{2}$$

Where $\Delta E$ = Energy Loss, $Re$ = Reynolds number, $Fr_o$ = initial Froude number, $G$ = the spacing between each cylinder in a cross-stream direction, $d$ = diameter of cylinder, $dn$ = vegetation thickness and $\theta$ = porosity. Since Froude scaling is commonly used for free surface gravity flows; thus pi-2 group which is Reynolds number, is ignored. Similarly ignoring all the constant parameters, the energy loss through two layers' vegetation is mainly a function of initial Froude number ($Fr_o$) and porosity of projected area in cross stream direction ($G/d$) of layer-2.

## 3. RESULTS AND DISCUSSION

### 3.1 Energy Loss Due to Vegetation

Hydraulic resistance including drag force by vegetation could reduce the energy of the flowing water. It leads to a lower inundation depth, inundation area and hydraulic force at the downstream. Therefore, the mechanism of energy dissipation effects of the forest need to be clarified. In this study, the specific energy is defined as the energy per pound of water at any section with respect to channel bed (Chow, 1959) is:

$$E = y + \alpha \frac{V^2}{2g} \tag{3}$$

Where $E$ is specific energy, $y$ is water level from the datum, $\alpha$ is coefficient to account for variation in velocity (considered as 1 in this study), $V$ is the mean velocity, and $g$ is the gravitational acceleration. The mean velocity $V$ is calculated using the continuity equation which is $V=Q/A$ where $Q$ is discharge and $A$ is the water cross-sectional area. The energy loss ($\Delta E$) through vegetation is the difference between specific energy upstream ($E_1$) and downstream of vegetation ($E_2$).

Without the vegetation model placed in the channel, the initial Froude number was 0.55-0.75. However, after mounting the vegetation model, the water profile was greatly changed. The water profiles at the center of channel of L1 and L1+L2 for three flow conditions are shown in Fig. 3. Depending upon the resistance offered by vegetation, the water level was raised on the upstream side of vegetation while on the downstream side the undular hydraulic jump was formed which contributed to energy loss to some extent (Pasha and Tanaka, 2016). However, in this experimental investigation, due to limited length of channel, the energy loss contribution by undular hydraulic jump was not calculated and only the total energy loss ($\Delta E= E_1 - E_2$) was figured out. Where $E_1$ is specific energy at forest front and $E_2$ is mean specific energy after formation of hydraulic jump where the flow is sub-critical. The mean values of $E_2$ were considered because of the fluctuations in water surface after the hydraulic jump.

The relationship between the amount of energy loss (cm) and the initial Froude number ($Fr_o$) is shown in Fig. 4. Fig. 4a and 4b compare the energy loss by layer-1 (L1) only and layer-2 (L2) only with the combined vegetation (layer-1 and layer-2, CO) respectively. In only L2 conditions (Fig. 4b), the total energy loss was the greatest for dense vegetation (L2-D) and least for sparse vegetation (L2-S). But, the L1 only (Fig. 4a) showed the opposite trend because the width vegetation was greatest for sparse vegetation (L1-S) as compared to dense arrangement (L1-D) under the same vegetation thickness condition of upper layer (layer-2). Under the condition, the resistance of layer-1 is larger in sparse condition than dense. With increase in $Fr_o$, the energy loss due to L2 only increased, while in L1 only, the energy loss increased slightly for the initial values of $Fr_o$ but it started to decrease slightly with further increase in $Fr_o$ (Fig. 4a). This is because, the emergent L1 vegetation at initial values of $Fr_o$ became submerged for the higher values of $Fr_o$ (Fig. 3I) which resulted in the decrease in energy loss by vegetation resistance. However, Fig. 4 shows that the combined energy loss by CO is highest for sparse vegetation and almost same for intermediate and dense vegetation. The larger vegetation width of L1 in sparse vegetation arrangement contributed to major energy loss in CO.

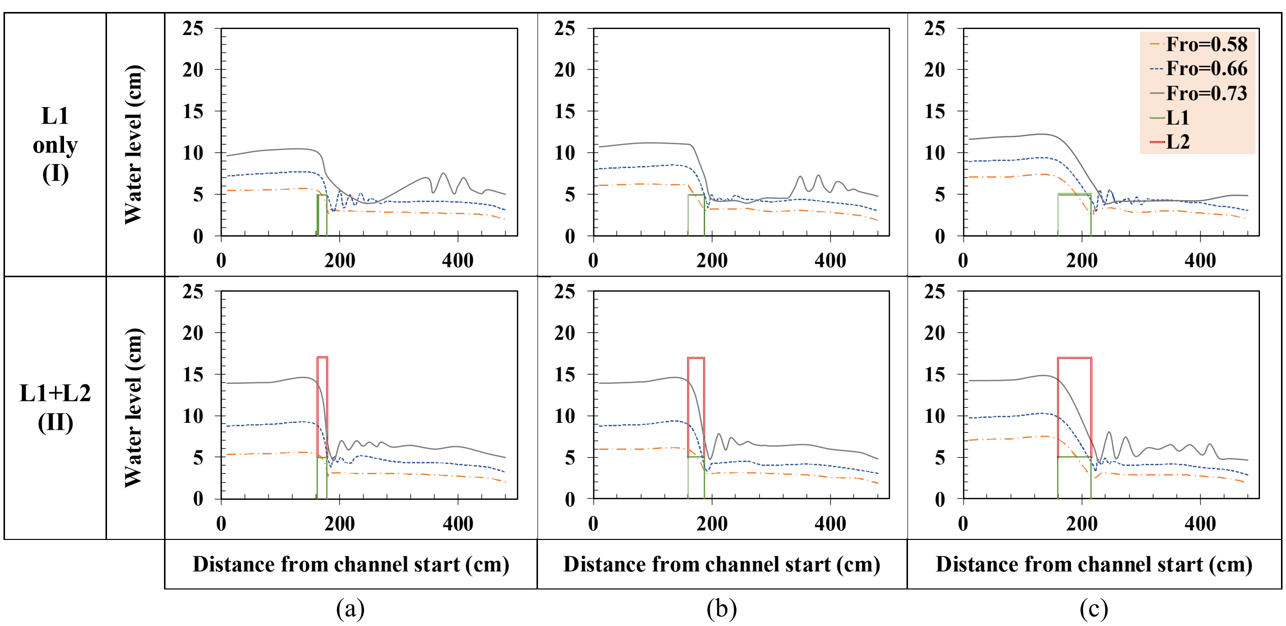
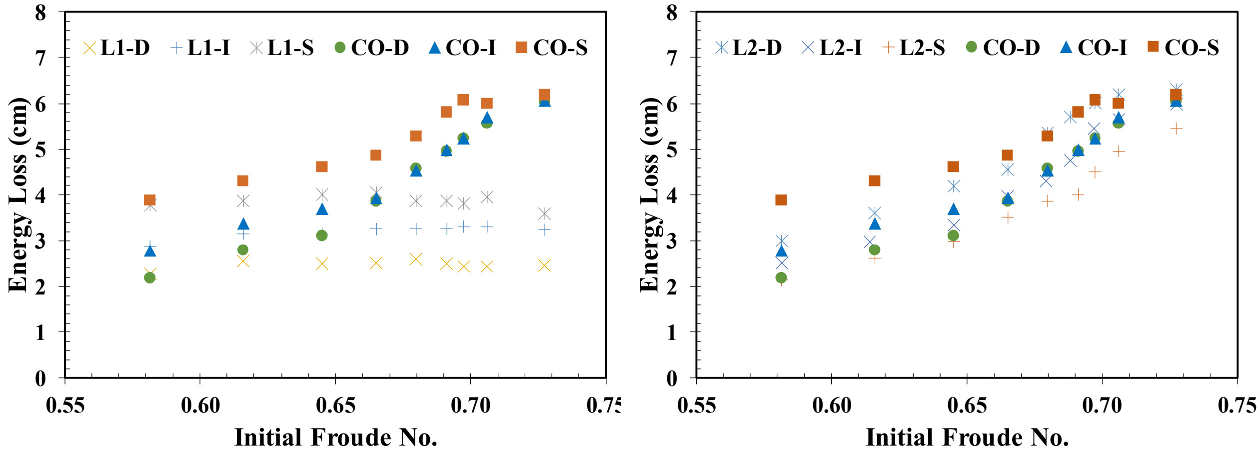



Fig. 3 Distribution of water level for layer-1 (L1) only and combined vegetation of layer-1 and layer-2 (L1+L2) (a) dense vegetation ($G/d$ = 0.25), (b) intermediate vegetation ($G/d$ = 1.09), and (c) sparse vegetation ($G/d$ = 2.13).




(a) (b)

Fig. 4 Relationship between energy loss and initial Froude number for different vegetation arrangement. Where L1 is layer-1 vegetation only, L2 is layer-2 vegetation only, CO is combination of layer-1 and layer-2 vegetation. D, I and S represents dense, intermediate and sparse vegetation, respectively.

It is clear from the experimental results that both the layers contributed to energy loss. However, the experimental results of total energy loss in a CO is less than the summation of separate losses due to L1 and L2 only. This shows that in numerical calculations, it may lead to inaccurate results when energy loss in each layer was simply added for calculating the total loss. Therefore, an additional coefficient needs to be added in numerical calculations to find the combined energy losses.

## 4. CONCLUSIONS

By increasing the density of vegetation comprising of layer-2 (L2) only, the energy loss increased. It also increased with increase in initial Froude number ($Fr_o$). However, in layer-1 (L1) only vegetation arrangement, the energy loss increased with increase in $Fr_o$ till the point before L1 got submerged; after that the energy loss started to decrease. In L1 only, the energy loss was highest in sparse vegetation since the porosity of vegetation was constant and the width of sparse vegetation was larger against constant vegetation thickness of layer-2 as compared to dense vegetation. In a combined arrangement (CO) i.e., L1 + L2, sparse vegetation also showed higher energy loss than dense vegetation owing to the greater contribution of L1 only. Further study is needed to investigate the non-linear effect between the layer-1 and layer-2.

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