# COMBINED EFFECT OF VEGETATION AND A BACKWARD FACING STEP ON ENERGY LOSS

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## 1. INTRODUCTION

The 2011 Great East Japan tsunami extensively destroyed parts of sea walls (tsunami gates, large embankments) (Suppasri et al., 2012) and coastal forest (Tanaka et al., 2013). The damage was also observed around Soma Port in Fukushima Prefecture where the high acceleration of tsunami water caused trees to break and wash away. Fig. 1 shows the situation of area near Soma Port before (left) and after (right) March 2011 earthquake. Extensive damage to houses located inland can be seen due to combined effect of tsunami currents and floating debris (driftwood produced from coastal vegetation, trucks lost from the port area, rubble of destroyed structures etc.). However, the vegetation belt (20-50m wide) which followed sudden backward facing step/drop of 2m just downstream of vegetation (Fig. 2) retained its position and trapped tsunami drifted debris. Some of the houses located inland and away from vegetation with a step survived which is also confirmed by Fig. 3. Thus, there is a possibility of greater energy reduction to tsunami flow due to added resistance offered by a step in combination to vegetation resulting in survival of houses to some extent.

Recently, Pasha and Tanaka (2016) conducted laboratory experiments to clarify the energy loss through vegetation not only by drag force but the downstream flow pattern change and confirmed increase in energy reduction with increasing vegetation density. The objective of the current study is to further clarify the energy loss mechanism by the combination of vegetation and a step. Flume experiments were conducted to determine the amount of energy loss through emergent vegetation of constant thickness, changing density, mounted over a step of constant height against different flow conditions. This study will help to design multiple protective measures for tsunami mitigation in future.

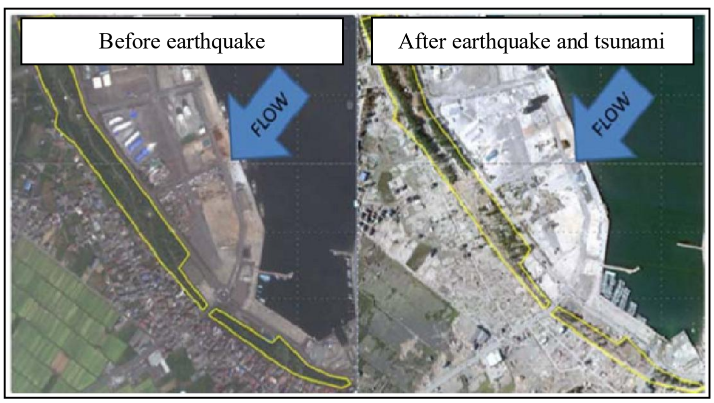


Fig. 1 Area near Suma Port before and after the 2011 Great East Japan tsunami (images taken from Google Earth)

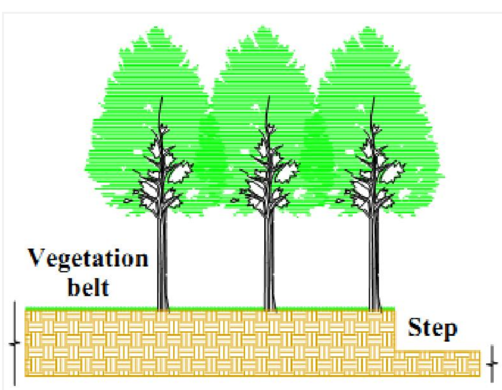


Fig. 2 Arrangement of vegetation with a backward facing step

Fig. 3 Some houses survived located away from vegetation with a step

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## 2. EXPERIMENTAL SETUP AND CONDITIONS

### 2.1 Experimental procedure and flume characteristics

Laboratory experiments for 3 different cases (Table 1) were conducted in a water flume (constant bed slope 1/500) which is 5m in length, 0.7m in width, and 0.5m in height, in Saitama University. The step height selected in the experiment was 2.5cm for a model scale - 1/100 referring to the existing step height at Soma Port, Fukushima Prefecture (Kanai and Tanaka, 2016). In the current study, as a first step, the initial Froude number ($F_o$, 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 (inland) by changing water depths from 3 to 7cm with an increment of 0.5cm. The water depth to step height ratio without vegetation model ranges from 1.20 to 2.80. After mounting the full width of vegetation model about 2.5m from the upstream inlet, the water level was measured throughout the center of the channel by using a rail mounted point gauge. The discharge value ($Q$) was measured using flow meter (Signet 8150 Flow Totalizer) and the mean velocity was computed using the measured water depth and discharge. 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

For a 1/100 scale model, the trees were modeled by wooden cylinders with a diameter of 0.004m set in a staggered arrangement, based on the average diameter of Japanese pine trees. Fig. 4a and Table 1 show the details of vegetation arrangement where $D$ is the distance between cylinders and $W$ is the width of vegetation model. The $G/d$ ratio greatly affects the flow structure and it classifies vegetation as sparse or dense, where $G$ represents the spacing between each cylinder in a cross-stream direction, and $d$ is the diameter of a cylinder (Fig. 4a). In Table 1, $D$ and $W$ were determined under same vegetation thickness: $dn$ which is defined by 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 width of forest ($W$) (Fig. 4a), (Shuto, 1987). In this study $dn$ was calculated as:

$$dn = \frac{2}{\sqrt{3}D^2} Wd \times 10^4 \qquad (1)$$

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

Table 1 Experimental conditions

| Case No. | $F_o$ | $G/d$ | $D$ (cm) | $W$ (cm) | $dn$ (No. cm) | Forest Type |
|---|---|---|---|---|---|---|
| 1 | 0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73 | 0.25 | 1 | 8.23 | 380 | Dense |
| 2 | 0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73 | 1.09 | 1.67 | 23.60 | 391 | Intermediate |
| 3 | 0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73 | 2.13 | 2.5 | 52.48 | 388 | Sparse |


(a) (b) (c)

Fig. 4 (a) Detailed arrangement of vegetation model (b, c) Vegetation model with 2.5cm step

### 2.3 Non-dimensional pi groups

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

$$f\left[\frac{b}{h_o}, \frac{\Delta h}{h_o}, \frac{h_s}{h_o}, \frac{V_o}{\sqrt{gh_o}}, \frac{V_1}{\sqrt{gh_1}}, \frac{\rho_w h_o V_o}{\mu}, \frac{G}{d}, dn, \frac{y_2}{y_1}, \frac{V_2}{V_1}, \frac{\Delta E}{E_1}\right] = 0 \qquad (2)$$

Where, $b$ = channel width, $h_o$ = initial water depth without forest, $\Delta h$ = backwater rise, $h_s$ = step height, $V_o$ = velocity at $h_o$, $F_o$ = Froude number at $h_o$, $F_{US}$ = Froude number on the upstream of forest against water depth $h_1$ and velocity $V_1$, $g$ = gravitational acceleration, $\rho_w$ = density of water, $\mu$ = viscosity of water, $y_1$ = minimum water depth during the jump, $y_2$

= mean water depth after the hydraulic jump, $V_2$ = mean velocity after hydraulic jump, $HGL$ = hydraulic grade line, $EGL$ = energy grade line, $E_1$ = specific energy at forest front, $E_2$ = mean specific energy after formation of hydraulic jump where the flow is sub-critical, $\Delta E$ = total energy loss ($E_1$-$E_2$) (Figs. 4 and 5).

Since width of channel ($b$) and step height ($h_s$) is same for every case during the experiment, so these pi groups can be ignored. In addition, viscosity and density of water are same for every case and Froude scaling is commonly used for free surface gravity flows; thus pi-6 group which is Reynold's number, is also ignored. Similarly ignoring all the constant parameters, the backwater rise and energy loss through vegetation with step is mainly a function of initial Froude's number ($F_o$) and forest density ($G/d$);

$$\frac{\Delta h}{h_o}, \frac{\Delta E}{E_1} = f\left[\frac{V_o}{\sqrt{gh_o}}, \frac{G}{d}\right] \tag{3}$$

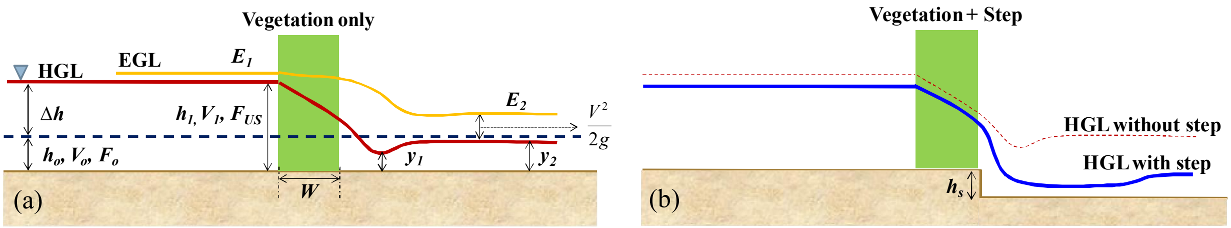


Fig. 5 Flow structure scheme and definition of various parameters (a) without step, (b) with step

## 3. RESULTS AND DISCUSSIONS

### 3.1 Upstream of vegetation model – backwater rise

The initial flow conditions without forest model placement in the channel was varied between $F_o$ = 0.55 and $F_o$ = 0.75. After placing the vegetation model in the channel, the water level at the vegetation front increased and the water surface slope inside the vegetation became larger. Against constant vegetation thickness *dn*, on the upstream of vegetation model, the backwater rise increases by increasing the density of vegetation due to higher vegetation resistance (Pasha and Tanaka 2016). Fig. 6 shows that relative backwater rise which is the ratio of backwater rise to initial flow depth, slightly increased with increasing the initial Froude numbers. This shows that initial flow depth has very little effect on the relative backwater rise for a given Froude number. However, the relative backwater rise on the upstream of vegetation slightly decreased in combined arrangement (vegetation + step, *VS*) as compared to only vegetation (*OV*). This is because, due to inertial forces and the decrease of bed resistance just behind vegetation, the step drags the stream of water slightly down just at the downstream of vegetation which also affected the upstream flow depth, thus constituently resulted in slightly lower backwater rise in combined arrangement.

### 3.2 Energy reduction behind vegetation

Hydraulic resistance and reflection of water from trees can reduce energy of flowing water, inundation depth, inundation area and hydraulic force behind the vegetation. The water passing through the vegetation becomes weaker which results in minimizing damage behind vegetation. As the density of vegetation increases (i.e., vegetation width becomes smaller), the maximum water level and maximum velocity behind the vegetation decrease (Iimura and Tanaka, 2012) resulting in significant energy loss. The specific energy which is defined as the energy per pound of water at any section of a channel measured with respect to channel bottom (Chow, 1959) is:

$$E = z + y + \alpha\frac{V^2}{2g} \tag{4}$$

Where; $E$ is specific energy, $z$ is height above datum (step height), $y$ is water depth, $V$ is velocity and $\alpha$ is coefficient to account for variation in velocity which is considered as 1 in this study. Since the flow is steady, therefore against the known discharge (Q) and measured water depth, mean velocity was calculated using relationship $V=Q/A$. The energy loss ($\Delta E$) through vegetation is the difference between specific energy upstream ($E_1$) and downstream of vegetation ($E_2$) (Fig 5a). It was observed during the experiments that as the water flow passes through the vegetation, the depth starts to decrease, and at the downstream of vegetation the depth becomes less than the critical depth which resulted in a formation of undular hydraulic jump. Pasha and Tanaka (2016) found that the undular hydraulic jump at downstream of vegetation also contributes to energy loss to some extent. However, adding step to vegetation in the current study reduced the intensity of jump and also increased the length of undular hydraulic jump even beyond the available length of channel for some cases. Thus, it was impossible to figure out energy loss contributed by jump in combined arrangement. Therefore, only the total energy loss (vegetation + hydraulic jump) was calculated i.e., $\Delta E = E_1 - E_2$. 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 $E_2$ are considered because of the fluctuations in water surface after the hydraulic jump.

Fig. 7 shows the relationship between the relative total energy loss ($\Delta E/E_1$) and the initial Froude number. In only vegetation conditions (*OV*), the total relative energy loss is the greatest for dense vegetation (*G/d*-0.25) and least for sparse vegetation (*G/d*-2.13) due to higher resistance offered in dense vegetation arrangement. However relative total energy loss almost remained constant when initial Froude number was increased from 0.55 to 0.75. With no vegetation arrangement, i.e., only step (*OS*), the energy loss is due to collision only which occurs at a step i.e., at a point of change in elevation. This energy loss starts to decrease with increase in water depth over a step of constant height (points of *OS* in Fig. 7). Since the loss due to collision starts to decrease with increase in water depth or with the increase in initial Froude number, thus, the total relative energy loss in combined arrangement (*VS*) also showed a lowering trend with increasing Froude number. However, the experimental results of total energy loss in a combined arrangement (*VS*) is less than the summation of separate losses due to only vegetation (*OV*) and only step (*OS*). This is due to the fact that the loss due to collision in a combined arrangement is less than only step condition, because at step location the water depth is higher in combined arrangement than in only step arrangement. Therefore, an additional coefficient needs to be added in numerical calculations to find the combined energy losses.

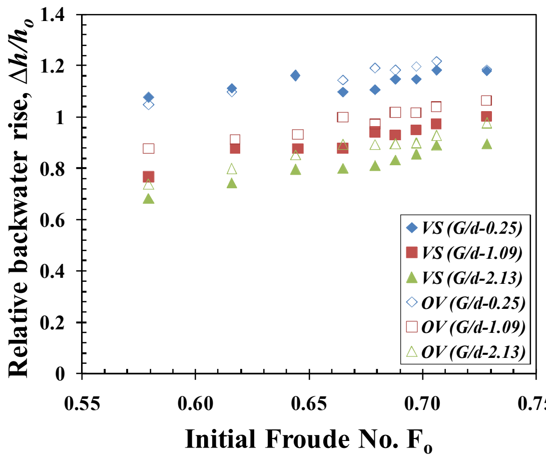


Fig. 6 Relative Backwater rise $\Delta h/h_o$ for both combined (*VS*) and only vegetation (*OV*) cases against three different vegetation densities.

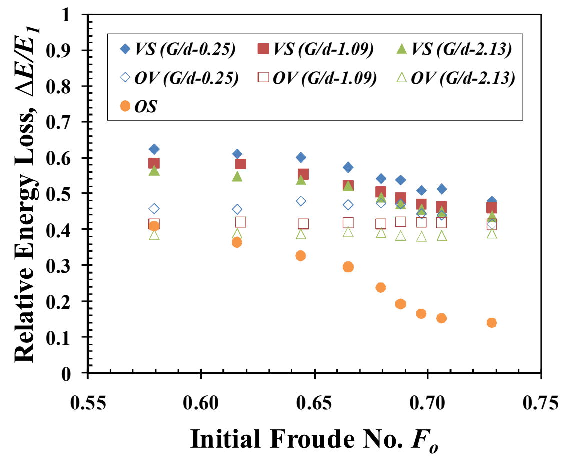


Fig. 7 Relative energy loss for combined (*VS*), only vegetation (*OV*) and only step (*OS*) arrangements against different vegetation densities.

## 4. CONCLUSIONS

On the upstream of vegetation without step (*OV*), backwater rise increased with increase in the initial Froude number and also with increase in the density of vegetation while keeping the vegetation thickness *(dn)* constant. However, adding step behind vegetation i.e., combined arrangement (*VS*) lowered the backwater rise slightly due to inertial forces. On the downstream side, energy was lost due to vegetation resistance and due to collision with the lower ground surface. In *OV* arrangement, the relative energy loss remained almost constant when initial Froude number was increased from 0.55 to 0.75 and was increased by increasing the vegetation density. Whereas, in a *VS* arrangement, the relative energy loss showed a lowering trend with increase in initial Froude number.

## ACKNOWLEDGEMENTS

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