ENERGY REDUCTION IN TSUNAMI THROUGH A DEFENSE SYSTEM COMPRISING AN EMBANKMENT AND VEGETATION ON A MOUND

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ABSTRACT

The countermeasure against tsunami inundation is drifting from only sea embankment to a hybrid system comprising embankment and coastal forest after the 2011 Great East Japan tsunami. Thus, the present experimental study investigated the defense system comprising an embankment (E) followed by a coastal vegetation (V) on a mound (M). The loss of energy head of the tsunami flow was examined with varying condition of mound length and forest density against different overtopping depths while keeping the mound height fixed. Different types of hydraulic jump were formed between E and V which also contributes to the energy loss significantly. The loss of energy head against the maximum h_o' = 0.48, (where, h_o' (non-dimensional overtopping depth) = overflowing water depth/ height of embankment) for the embankment followed by vegetation on a mound (EVM) was found to be 43%, whereas it was found to be 23% for the embankment followed by mound (EM) only. Moreover, the energy of the flow against the considered range of h_0' was significantly reduced by 43%–65% in case of EVM, whereas it was reduced by 23%–64% in case of EM. An exponentially decreasing trend in energy dissipation was observed with increase in h_0' for both cases because the effect of energy reduction by hitting the ground became relatively low with the increase in overflowing water depth.

Keywords: *hybrid defense system, coastal forest, overtopping flow, hydraulic jump, tsunami mitigation.*

1. INTRODUCTION

In 2011 the Great East Japan Tsunami (GEJT) has destroyed severely the coast of Tohoku and Kanto Districts in Japan and caused fatal damage to the human lives, buildings and coastal forest (Tappin et al., 2012; Tanaka, 2012). For mitigating the extreme events caused by tsunami, the strategy of tsunami mitigation has been drifting from single to compound defense system comprising both natural and artificial measures. Several studies introduced different configurations of compound defense systems like moat and embankment (Fadly and Murakami, 2013), embankment, moat, and vegetation (Zaha et al., 2018) and embankment, vegetation (Rashedunnabi and Tanaka, 2019).

Coastal vegetation acts as a bio-shield which prevents the coastal regions from extreme events like tsunami. An experimental study by Pasha and Tanaka (2017) showed that, the maximum energy reduction of tsunami current could be obtained by providing a dense forest at emergent condition but in real scenario it could be difficult to implement a dense forest. Anjum and Tanaka (2019) investigated the effectiveness of discontinued double layered vegetation but there might be space limitation in the coastal regions. A recent study by Rashedunnabi and Tanaka (2019) clarified the mitigation effect of compound defense system combining a coastal embankment followed by a coastal vegetation by flume tests. They showed that the different configurations of vertically double layered vegetation can effectively reduce the tsunami energy and could form different types of hydraulic jump which contributes further reduction on tsunami energy. They discussed that, when hydraulic jumps lie on slope of the embankment (i. e., type-B) it was safer for defense structures based on erosion phenomena, because in coastal regions the embankment was protected. In this study, a mound was introduced for the plantation of vegetation, and to generate hydraulic jumps on the downward slope of the embankment. Whereas it was also expected that, the mound might contribute on further energy reduction of tsunami current. However, there is few studies that clarifies the flow structures within hybrid defense system. Also, the configuration of coastal vegetation in the hybrid defense system still needs to be optimized.

Therefore, the main objective of this study is to evaluate a hybrid defense system comprising a sea embankment model (E) followed by coastal vegetation model (V) over a mound model (M). To clarify the effectiveness, different density of single layer emergent vegetation models was tested under supercritical condition over M. In addition, a sea embankment model (E) followed by a mound model (M) (EM) cases were also performed to differentiate the significance of vegetation over mound model in reducing tsunami energy.

2. METHODOLOGY

2.1 Experimental and flow conditions

A series of laboratory experiments were conducted in a steady state flume channel having dimensions of 14 m × 0.5 m × 0.7 m at Saitama university, Japan. In order to obtain the supercritical flow conditions, a constant bed slope of 1/200 was set in the flume, since the tsunami flow in some of the coastal regions was supercritical (Rashedunnabi and Tanaka, 2019). A roller-mounted point gauge was used to measure the water depth throughout the center of the flume channel. The water depth was measured throughout the mitigation system depending upon the variation in the water surface but in the cases of the fluctuations due to hydraulic jump, several readings were taken and finally averaged at a fixed point. To determine the depth averaged velocity i.e., U (m/s), continuity equation, $U = Q/(hb)$, (where Q is the discharge (m^3/s), h is the water depth and b is the flume width) was adopted. In this experiment, six non-dimensional overtopping depths [h_o' = overflowing water depth (h_o)/embankment height (H_E)] of different initial Froude numbers ($F_r = U/(gh_i)^{0.5}$) were selected under supercritical flow conditions.

2.2 Model design and vegetation configurations

A physical model scale of 1/100 was selected, for the experimental models. For the vegetation models, the Japanese Pine tree with an average diameter of 40 cm was available in Sendai (Tanaka, 2012), was taken as a reference tree and modelled by wooden cylinder having diameter of (d) 0.4 cm. The cylinders in V were designed in a staggered arrangement. The width of vegetation (W_V) and center to center distance (D) between trees was defined by forest density (G/d, where G = clear spacing of each cylinder in cross-stream direction, d = diameter of cylinder) and vegetation thickness ($dn = 2W_V d((3D^2)^{0.5}) \times 10^2$) of 90 (number cm) on real scenario. In this paper, the vegetation models are represented by porosity ($Pr = 1 - n_t \pi d^2/4$, where n_t is the number of trees per unit area). The vegetation conditions were shown in Table 1. A wooden embankment was scaled down to height of 14.5 cm and side slope of 1:2 and modelled representing an embankment height of 14.5 m, proposed for the implementation in the Iwate, Fukushima Prefecture in Japan (Rashedunnabi and Tanaka, 2019). The M was modelled to a non-dimensional mound height [h_m' = mound height (h_m)/ H_E] of 0.19 and side slope of 1:2. The non-dimensional mound lengths [l_m' = mound length (l_m)/ H_E] were 1.32, 1.78, and 4.31. The l_m were varied according to the different W_V. In this study, the gap (S) kept between E and M was 50 cm. The experimental setup is illustrated in Figure 1 (i).

Table 1 Experimental conditions and vegetation configuration

Case No.	Forest type	Initial Froude No. "F_r"	h_o'	D (cm)	G/d	Porosity "P_r"	l_m'	W_V (cm)
1	Only Embankment	1.02, 1.29, 1.44,1.49, 1.52, 1.56	0.07, 0.16, 0.26, 0.34, 0.44, 0.48		-	-	-	-
2	Intermediate	1.02, 1.29, 1.44,1.49, 1.52, 1.56	0.07, 0.16, 0.26, 0.34, 0.44, 0.48	1.67	1.088	0.95	1.32	5.41
3	Sparse	1.02, 1.29, 1.44,1.49, 1.52, 1.56	0.07, 0.16, 0.26, 0.34, 0.44, 0.48	2.5	2.125	0.98	1.78	12.18
4	More Sparse	1.02, 1.29, 1.44,1.49, 1.52, 1.56	0.07, 0.16, 0.26, 0.34, 0.44, 0.48	5	5.25	0.99	4.31	48.75

2.3 Classification of hydraulic jump

The types of different hydraulic jumps were classified based on the formation of hydraulic jump in between E and V over M. When the hydraulic jumps were formed in the gap *(S)* i.e., between the toe of the E and V, it was defined as type-A jump (Chanson, 2004) and on the other hand, when a submerged hydraulic jump is formed and the position of its starting point i.e., the toe of the submerged hydraulic jump lies on the downward slope of the embankment, it was classified as a type-B jump (Chanson, 2004). The classification of different types of hydraulic jumps were illustrated in Figure 1 (ii & iii), where h_0 is the overflowing water depth, P_j is the position of the jump.

2.4 Energy loss

In the present study, to assess the effectiveness of the hybrid defense system as a function of mitigation from the effect of tsunami, the energy head and the total energy reduction (Chow, 1959) was estimated based on following:

$$E = h + \alpha \frac{V^2}{2g} \tag{1}$$

$$\Delta E\ [\%] = \frac{(E_1 - E_2)}{E_1} \times 100 \tag{2}$$

where E is the specific energy, ΔE is the total energy reduction, E_1 is the specific energy at section-1, E_2 is the specific energy at section-2 as shown in Figure 1 (ii & iii), h is the depth of water, V is the velocity and α is the co-efficient of energy. In the present study the value of α was taken as 1, because the vegetation was single layer forest.

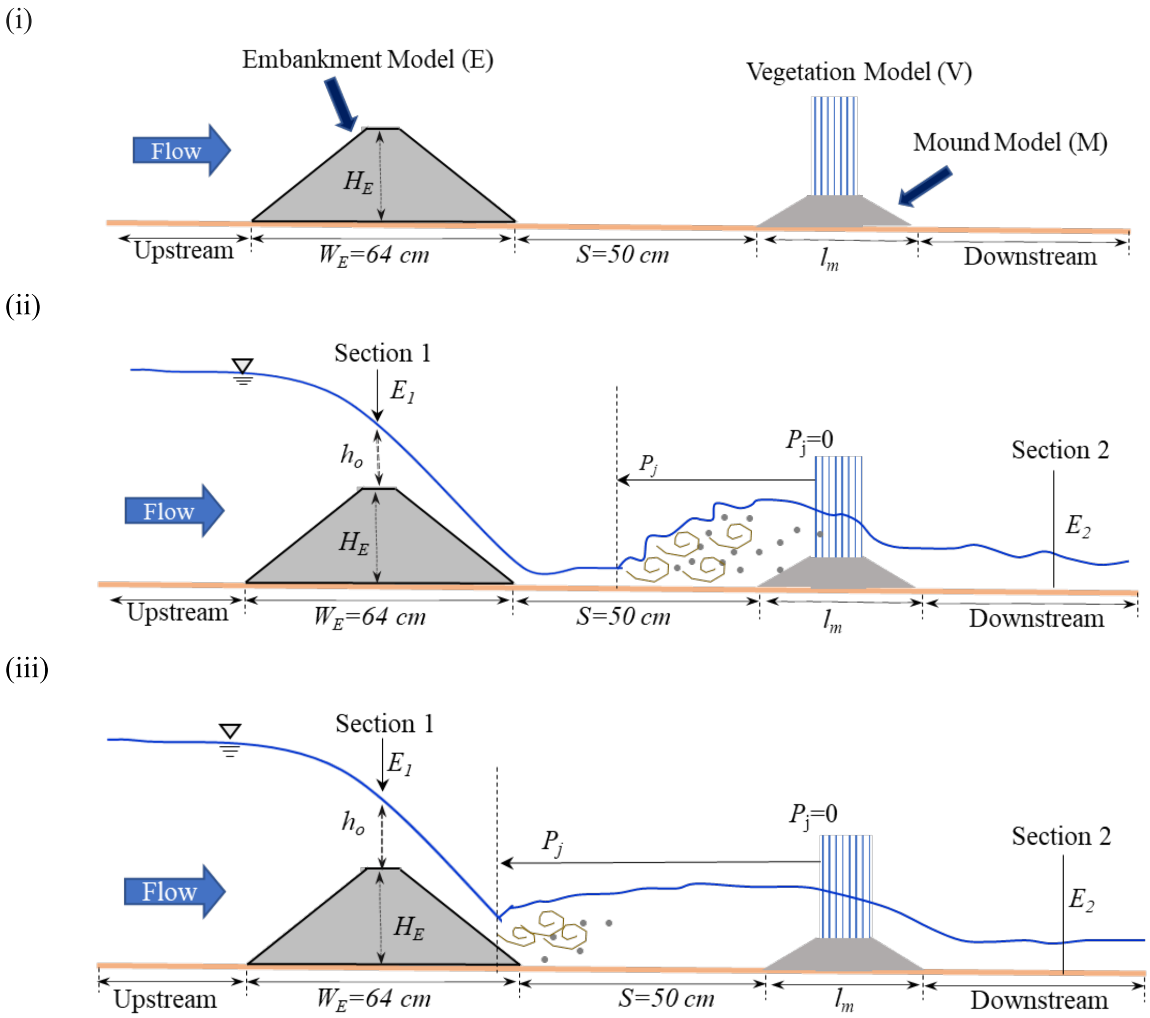


Figure 1. Schematic diagram of Experimental setup (i) and different types of hydraulic jump (ii) type-A, (iii) type-B

3. RESULT

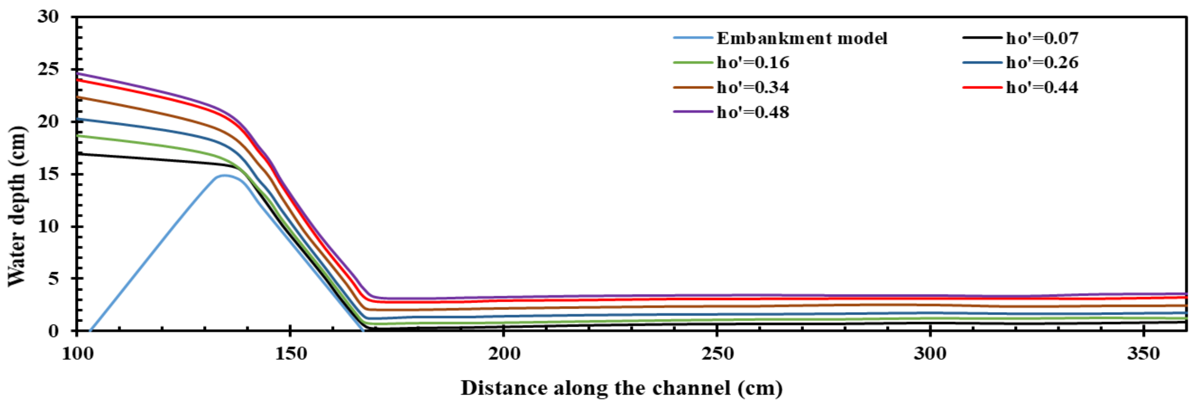
3.1 Changes of flow variations within hybrid defense system

3.1.1 Effect of mound on hydraulic jump formation

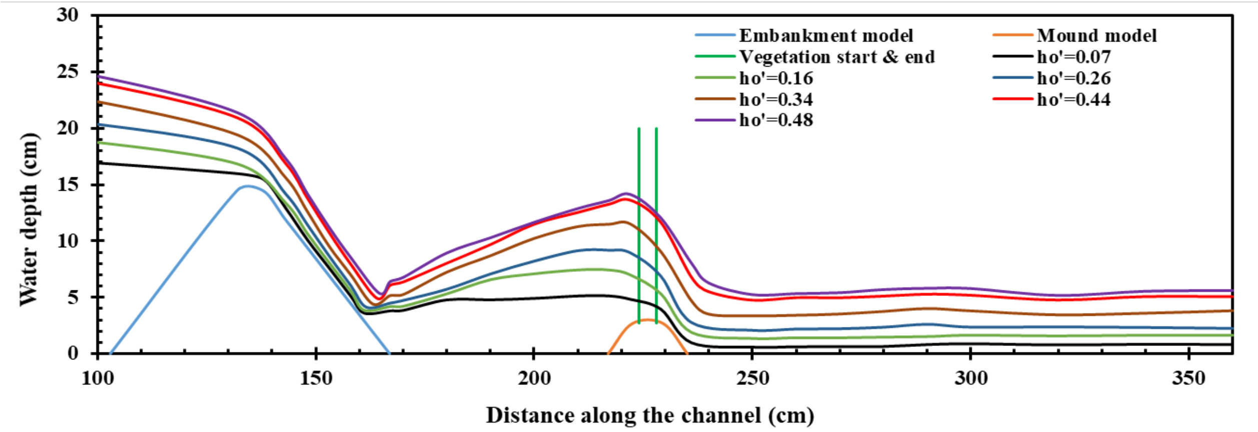
In OE case i.e., case 1, the overflowing water depth was gradually decreased as the flow approached to the toe of E and it remains flat throughout the downstream section (Figure 2 (i)). Figure 3 (ii) represents the different types of hydraulic jumps for EM cases. After installing M, when the water flows through the spaces in between the E followed by M (EM) due to the effect of M, the flow experienced a type-B jump for the lowest two h_o', i.e., h_o'= 0.07 & 0.16 (as shown in Figure 3 (ii)) in cases 2 to 4. This is due to the reason that the reflection offered by the height of M. However, with the further increase of h_o', i.e., the highest four h_o', the flow was swept out and no hydraulic jump was formed for the cases 2 to 4. These phenomena occurred because the reflection offered by the height of M was not significant enough to generate any jump to the higher specific energy of the flow. The same phenomena were observed by Tanaka and Igarashi (2016) in their multiple defense system of two embankments.

3.1.2 Effect of vegetation over mound on hydraulic jump formation

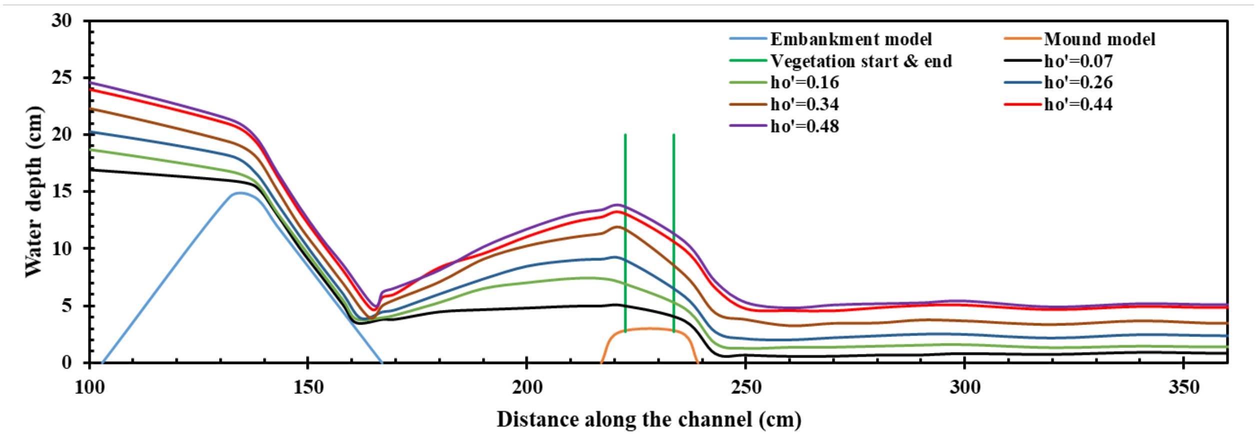
After the placement of the vegetation models in different configurations, a significant change on the flow structure was observed and the resulted water surface profiles for case 2 to 4, were presented in Figure 2 (ii), (iii) & (iv), against the varying condition of h_0'. The classification of different types of jumps were shown in Figure 3 (i). In the case 2 and 3 i.e., for G/d = 1.088 & 2.125; hydraulic jumps were generated on the downward slope of the E (type-B in Figure 3 (i)) for all the considered flow conditions (as shown in Figure 2 (ii), (iii) & (iv)). This is because of the combined reflection from the upstream slope of M and the resistance offered by V. However, in case 2 and 3, with the increase of h_o', the starting position of jump was moved towards the toe but still remains on the slope of downward face of the E and ultimately classified as type-B jump (Figure 2 (ii) & (iii)). In addition, the backwater rise just in front of vegetation in the intermediate case, i.e., G/d = 1.088; was slightly higher because the spacing of the cylinders in the case was much closer than other cases (Figure 2 (ii)). On the other hand, in the More Sparse case i.e., G/d = 5.25; for the first three h_o' i.e., h_o' = 0.07, 0.16, 0.26; type-B jump was formed and the rest three h_o' i.e., h_o' = 0.34, 0.44, 0.48; type-A jump was formed because in more sparse case the spacing cylinders was much larger so that water passes quickly and the frictional forces offered by the cylinders was not strong enough to the specific energy of the overtopping flow depths Moreover, the gradient of water surface slope inside the V was steeper in intermediate case whereas in more sparse case slope was gradually decreasing (Figure 2 (ii)). Which implies that the steep water surface slopes have a possibility to increase the scouring just behind of the V. On the downstream of the V, water passes smoothly and there is no undulation even no hydraulic jump was formed. This might be the effect of the slope of the M. In coastal areas, the embankments are made of concrete if type-B jump was formed then the possibility of failure of defense structure was less. But if the jump was formed in the gap between embankment and vegetation (type-A), then due to the erosion the vegetation might be washed out (Rashedunnabi and Tanaka, 2019). Based on this perspective the configuration should be arranged in such a way, so that type-B jump can easily form. When the vegetation was on the top of the second embankment (Tanaka and Igarashi, 2016), type-B jumps were formed for the lower overtopping depths, but flow is swept out for the higher overtopping depths. In this case, there is a significant chance that the vegetation would be washed out. On the other hand, in the case of embankment followed by land piles, type-A hydraulic jump was observed for the lowest overtopping depths, and a nap flow was observed with the increased overtopping depth (Igarashi et al., 2018). This phenomenon could be dangerous because due to erosion, the piles could be broken. But when a full length of vegetation would be provided, it can easily generate type-B hydraulic jump which ensures safety of the defense system.



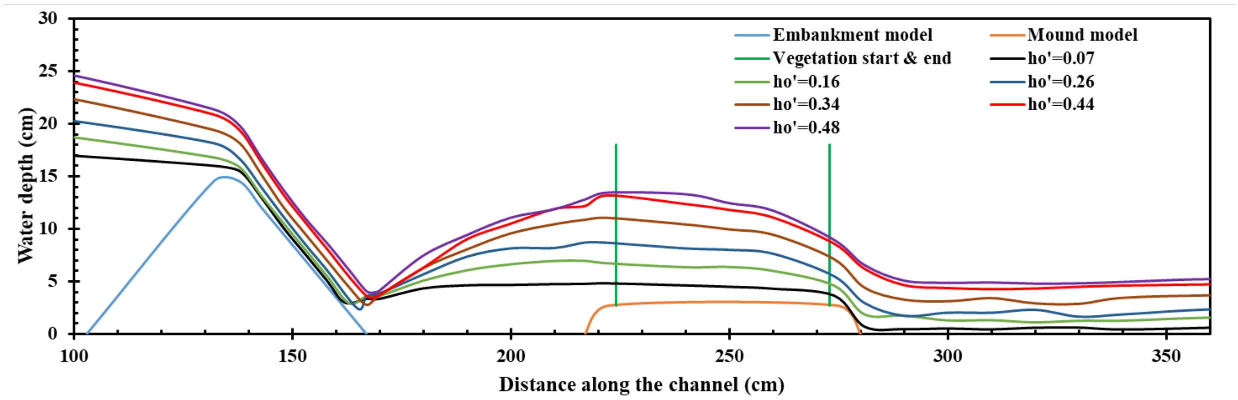
(i)



(ii)

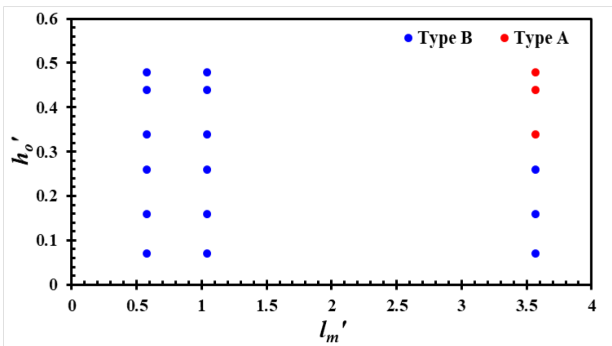


(iii)

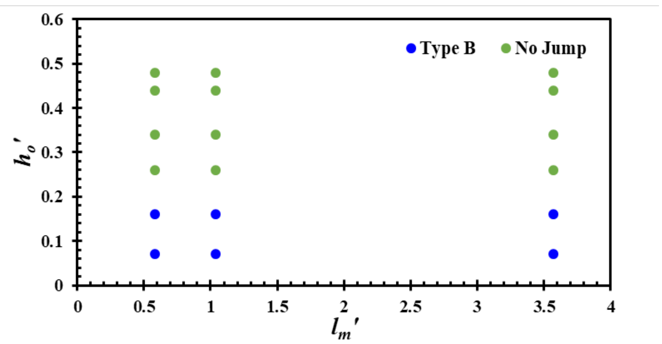


(iv)

Figure 2. Flow structure around hybrid defense system against varying h_o', (i) case 1, (ii) case 2, (iii) case 3, (iv) case 4



(i)



(ii)

Figure 3. Types of hydraulic jumps against varying h_o', (i) with vegetation (EVM), (ii) without vegetation (EM)

3.2 Energy loss in the defense system

3.2.1 Effect of mound on energy reduction

The total loss of relative energy for case 1 (the lowest h_o', *i.e.*, h_o'= 0.07) was found to be 53% and with the further increase of h_o' an exponentially decreased trend was observed (as shown in Figure 4 (ii)). For the maximum h_o' (= 0.48), the energy reduction was found about 3%. On the other hand, for EM cases i.e., case 2 to 4, the loss was 64%. Moreover, a sharp decreasing trend on energy reduction was observed in all cases and finally it was reduced to 23% in case 2, and 26 % in case 4. However, due to the length of mound in case 4, the energy loss was slightly higher about 1% to 3%, compared with case 2.

3.2.1 Effect of vegetation on energy reduction

After placement of V on M, the loss of energy was raised significantly due to the combined effect of M and V. For EVM cases i.e., case 2 to 4; energy reduction was about 65% for h_o'= 0.07 (Figure 4 (i)). However, a gradually decreasing trend was observed for all the EVM cases with the further increase of h_o' and ultimately for the maximum h_o', i.e., h_o'= 0.48 the energy reduction was reduced to 43% to 45%. The effect of V was very small for h_o'= 0.07 and 0.1; its mainly the effect of M but with the increasing of h_o' the effect of V was clearly noticed. However, the effect of V for the rest four h_o' was found to be about 1% to 20% in EVM cases. The intermediate case gives more energy reduction about 1% to 4% compared to the other cases due to the reason that the turbulence was higher because of closer spacings of cylinders, which resulted an increased water depth at the downstream.

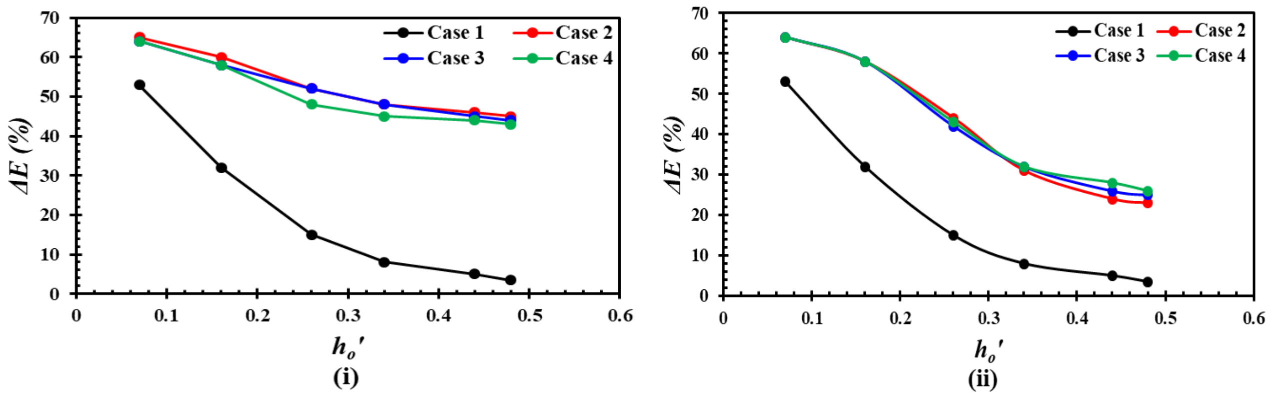


Figure 4. Energy reduction of hybrid defense system against varying h_o', (i) with vegetation (EVM), (ii) without vegetation (EM)

4. CONCLUSIONS

The conclusions of the present study are as follows:

- Within the hybrid defense system i.e. EVM, a submerged hydraulic jump i.e. type-B jump, was formed on the embankment slope due to the vegetation resistance for almost all the cases against the considered range of overtopping flow depths. Whereas, such flow structure was not clearly observed in EM and OE cases. Furthermore, the EVM defense system successfully controls the hydraulic jump position over the embankment slope that also contributes in flow energy reduction.
- EVM cases reduced the flow energy about 43%–65%, whereas the corresponding reduction for EM cases were found to be 23%–64%. Hence, due to the formation of type-B jump within the defense system, the vegetation cases further reduced the flow energy by approximately 1–20%, in which the energy reduction by the intermediate vegetation configuration is found to be significant.

The present study explains basic flow structures and its effect on energy reduction, of a defense system comprising a seaward embankment and a vegetation on a mound under fixed bed condition. However, further investigation considering the effect of flow on the scouring phenomena around the defense structures is required under moveable bed condition.

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