TSUNAMI HAZARDS: IMPACT MITIGATION CHARACTERISTICS OF COASTAL VEGETATION

Harini Thalagala[1], Harsha Ratnasooriya[2], Samantha Hettiarachchi[3]

[1]Postgraduate Student, Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka.
[2]E-mail: harini999@gmail.com
[3]Telephone: +94-11-2650567-8 (Ext.2115) ; Fax: + 94-11-2651216

[2]Senior Lecturer, Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka.
[1]E-mail: ahrr@civil.mrt.ac.lk
[1]Telephone: +94-11-2650567-8 (Ext.2005) ; Fax: + 94-11-2651216

[3]Professor, Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka.
[1]E-mail: sslh@civil.mrt.ac.lk
[2]Telephone: +94-11-2650567-8 (Ext.2114) ; Fax: + 94-11-2651216

Abstract: In the aftermath of the Indian Ocean tsunami in 2004 the protection offered by coastal vegetation became evident in many countries affected and the role of coastal green belts in mitigating tsunami impacts has now been clearly recognized. Coastal green belts also attract attention as an environmental friendly and cost effective measure of impact mitigation. In this study, expanding the previous works conducted, further experiments were conducted to assess the energy dissipation and impact mitigation characteristics of coastal vegetation in detail. The resistance offered towards the flow which depends on the characteristics of individual plants and characteristics of the vegetation as a whole were assessed. Tests were conducted in a hydraulic flume in which vegetation was represented by geometrically similar small scale models. The energy dissipation of flow through vegetation was determined under steady flow conditions and reduction in inundation extent was assessed under unsteady flow conditions. Energy dissipation levels up to 48 % and inundation reduction levels up to 35 % were obtained in the experiments which clearly indicate the effectiveness of coastal green belts in tsunami impact mitigation. The dependence of the level of inundation reduction on the level of energy dissipation was also investigated.

Keywords: Tsunami, Hazards, Mitigation, Coastal, Vegetation

1 Introduction

Sri Lanka was unfamiliar with major natural hazards such as tsunamis until the Indian Ocean Tsunami (IOT) in 2004 which severely damaged the coastal areas causing a large number of casualties and property damage. Although tsunamis affecting the country have been rare, the IOT in 2004, subsequent tsunami alerts in 2005 and 2007 as well as the historical records of tsunami events in the past have highlighted the exposure of Sri Lanka to such hazards and the need of developing appropriate impact mitigation measures has clearly been identified.

Following the IOT disaster, the protection offered by coastal vegetation became evident in many countries affected (Kathiresan and Rajendran, 2005 and Tanaka et al, 2007) and the role of coastal green belts in mitigating tsunami impacts has now been clearly recognized. Coastal vegetation also attracts attention as an environmental friendly and cost effective measure of impact mitigation. The development and utilization of coastal green belts would thus be effective as an impact mitigation measure for such infrequent hazards affecting a widespread area.

In this research, the preliminary experimental studies on the resistance offered by coastal vegetation to tsunami overland flow were expanded to determine the energy dissipation characteristics and reduction in inundation extent in detail, in order to assess the effectiveness of coastal green belts in tsunami impact mitigation.

2 Resistance Offered by Coastal Vegetation

The flow through vegetation can be considered as a flow around non-streamlined solid bodies from a hydraulic engineering point of view. In such flow, both drag and inertia forces contribute to the resistance offered by solid bodies. In the tsunami induced overland flow caused by long waves of large periods, the drag force is dominant in comparison to the inertia force (Tanaka et al, 2007) and it can be considered that the energy dissipation of flow through vegetation is mainly caused by drag resistance.

The drag resistance F can be defined as,

$$F = \frac{1}{2}\rho C_D A U^2 \qquad (1)$$

Where, ρ = Density of fluid
C_D = Drag coefficient
A = Projected area of solid body
U = Velocity of flow

The drag coefficient depends on the shape of the body and the characteristics of the wake formed by the separation of flow around the solid body. The variation of drag coefficient can be expressed in terms of the Reynolds number Re, which for a circular body can be expressed as,

$$\mathrm{Re} = \frac{UD}{\nu} \qquad (2)$$

Where, D = Diameter
ν = Coefficient of kinematic viscosity of fluid

3 Drag Resistance and Vegetation Characteristics

In a flow through group of solid bodies, as the wakes formed by upstream bodies are disturbed by downstream bodies, the total resistance would be influenced by the number of bodies and the distribution of such bodies. Thus the drag resistance offered by vegetation would likely to depend on the characteristics of individual plants as well as the characteristics of vegetation as a whole, namely density/spacing, extent and distribution pattern.

Based on field studies, three main components of a plant structure, aerial root system, stem and branch structure that may offer varing degree of resistance have been identified (Ratnasooriya et al, 2008). The influence of these three components has been considered together with depth of inundation, by identifying four categories of vegetation as indicated in Table 1.

Table 1: *Categories of Vegetation*

Category	Inundation		
	Aerial root system	Stem	Branch Structure
I	No	Yes	No
II	No	Yes	Yes
III	Yes	Yes	No
IV	Yes	Yes	Yes

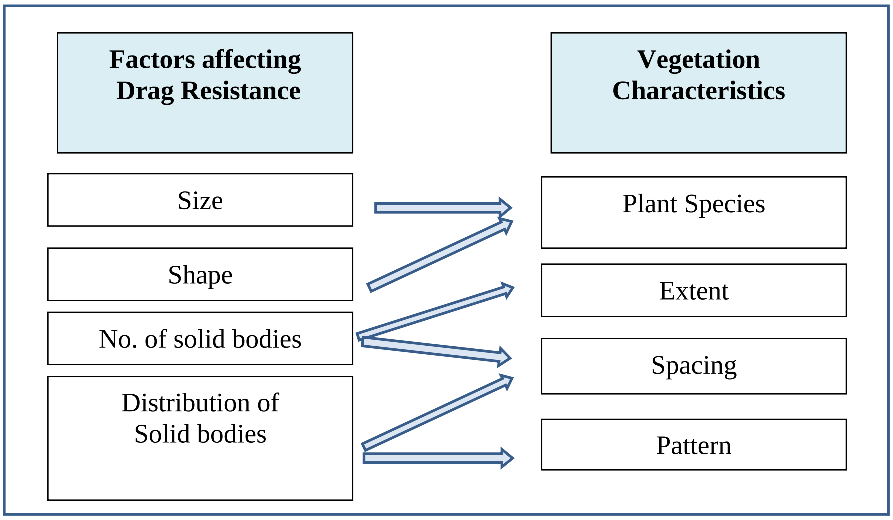

Figure 1: *Drag resistance and vegetation characteristics*

4 Physical Model Study

Detailed experimental studies were conducted to assess energy dissipation characteristics and to determine the reduction in inundation distance in which the vegetation was represented by geometrically similar small scale (approximately 1:100) models. Similar to preliminary studies (Ratnasooriya et al, 2008); this study was conducted in a hydraulic flume of length 10 m, width 30 cm and depth 30 cm.

The energy dissipation of flow through vegetation was determined under steady flow conditions. The experimental set up is shown in Figure 2(a) and Figure 2(b).

Figure 2(a): *Experimental set-up*

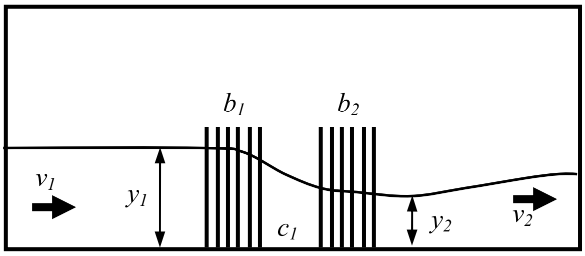

Figure 2(b): *Experimental set-up*

For the steady flow shown in Figure 2(b), neglecting frictional head loss and the bed slope over the short length through vegetation, the head loss due to the presence of vegetation *dH* can be expressed as:

$$dH = H_1 - H_2 = (y_1 - y_2) + \frac{1}{2}(V_1^2 - V_2^2) \qquad (3)$$

Where, H_1 = total head upstream of vegetation
H_2 = total head downstream of vegetation
y_1 = upstream depth of flow
y_2 = downstream depth of flow
V_1 = upstream velocity of flow
V_2 = downstream velocity of flow
g = acceleration of gravity

By replacing the velocity terms with discharge;

$$dH = (y_1 - y_2) + \frac{Q^2}{2gB^2}\left[\frac{1}{y_1^2} - \frac{1}{y_2^2}\right] \tag{4}$$

Where, Q = rate of flow
B = width of the flume

Hence the energy loss can be determined by % head loss with respect to total head of incoming flow H_1, by depth and discharge measurements.

The reduction in inundation extent was assessed under unsteady flow conditions where mass of water was released over a sloping surface as in dam break problem. The experimental set up is shown in Figure 3(a) and Figure 3(b).

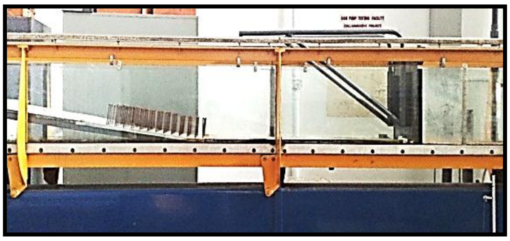

Figure 3(a): *Experimental set-up*

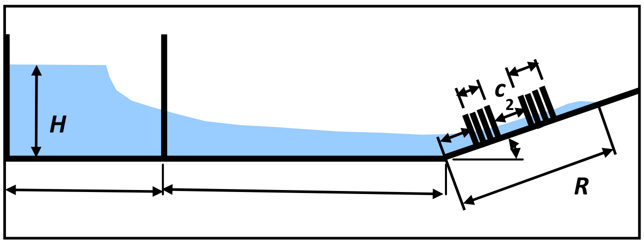

Figure 3(b): *Experimental set-up*

The reduction in inundation distance due to existence of vegetation, *dR* can be expressed as,

$$dR = \frac{(R - R_0)}{R_0} \tag{5}$$

Where, R_o = inundation distance without vegetation
R = inundation distance with vegetation

The inundation of the stem of plants without the aerial root system (Category I), perhaps representing the most common type of coastal vegetation, was considered in the tests. The plants were represented by nails and different diameters were used to represent variety of plant sizes. Parameters such as extent, density and grid pattern were varied to assess the influence on energy dissipation and impact mitigation.

5 Results and Analysis

Tests were considered for a number of vegetation configurations and the results are summarized in Table 2. The comparison of steady flow test results with unsteady flow test results for same vegetation configurations was presented where *dH/H %* represents the % head loss with the presence of vegetation and dR/R_0 *%* represents the % reduction in inundation distance over a sloping surface due to presence of vegetation.

Table 2: *Physical model test results*

Test No	Extent (cm)	Spacing (cm)	Diameter (mm)	Steady Flow		Unsteady Flow					
						θ = 1:7.5		θ = 1:10		θ = 1:12.5	
				S	**U**	**S**	**U**	**S**	**U**	**S**	**U**
				dH/H %	*dH/H %*	*dR/R %*	*dR/R %*	*dR/R %*	*dR/R %*	*dR/R %*	*dR/R %*
1			3	33.2	30.7	21.5	21.8	23.3	22.5	24.7	22.7
2		2	4	40.1	35.5	30.0	26.9	30.3	28.1	31.0	28.5
3			5	48.7	41.3	35.6	31.2	37.8	33.1	36.5	33.5
4			3	23.2	20.1	22.5	23.0	22.2	21.8	22.1	20.4
5	48	3	4	25.1	22.0	28.8	25.1	26.9	25.9	25.5	24.3
6			5	29.7	26.0	28.9	28.2	27.8	27.8	28.6	27.3
7			3	17.0	16.6	19.0	12.5	18.8	17.7	18.0	15.2
8		4	4	17.5	16.2	22.8	19.7	15.3	20.0	22.6	19.8
9			5	22.6	18.8	27.2	25.0	25.5	23.4	26.4	23.2
10			3	29.5	26.8	22.5	22.9	21.1	21.5	20.4	19.3
11		2	4	34.6	30.9	27.7	28.1	27.0	25.9	25.5	23.4
12			5	43.5	39.0	31.0	31.9	31.8	29.1	31.8	28.2
13			3	17.7	16.1	24.9	21.8	20.4	19.9	19.8	16.4
14	36	3	4	21.2	18.4	26.6	24.3	24.9	22.2	22.7	20.2
15			5	27.1	22.7	25.7	27.3	26.5	25.5	23.7	24.6
16			3	14.2	15.5	18.1	15.4	15.7	13.9	14.2	12.6
17		4	4	13.2	12.7	21.1	17.5	19.9	18.7	18.1	17.5
18			5	19.1	18.0	25.7	21.7	22.8	19.7	20.2	20.7
19			3	23.3	19.6	21.7	20.9	20.0	20.5	17.7	17.9
20		2	4	29.6	25.4	24.7	23.9	23.3	24.8	22.7	20.7
21			5	37.0	33.4	29.7	26.6	27.3	26.5	25.4	24.7
22			3	13.8	11.7	19.3	17.6	18.5	18.5	31.4	14.5
23	24	3	4	16.1	14.2	21.4	20.1	22.4	20.8	20.1	16.9
24			5	21.3	18.3	25.9	23.6	24.6	23.7	26.9	19.7
25			3	9.9	11.4	13.3	10.7	13.9	11.3	14.9	8.9
26		4	4	11.1	9.6	15.3	15.0	16.5	15.0	14.3	11.9
27			5	15.4	13.2	20.0	16.8	20.9	18.6	17.9	14.9
28	12		3	17.7	16.1	21.7	18.9	19.1	18.5	20.3	13.4
29		2	4	22.5	19.6	23.0	21.5	20.0	20.5	15.6	16.5
30			5	29.7	24.1	21.9	23.4	21.0	22.1	17.7	17.5
31			3	9.9	10.2	13.1	12.9	13.2	10.6	9.3	8.6
32		3	4	12.0	10.9	15.6	13.1	15.6	12.9	18.2	10.0
33			5	16.9	13.4	21.0	17.8	20.7	16.4	23.0	12.5

34			3	8.2	10.0	6.9	7.6	11.2	8.9	6.3	6.0
35		4	4	7.1	8.4	11.4	7.6	9.4	11.5	7.6	6.6
36			5	9.8	9.7	14.0	11.4	13.2	12.3	10.6	8.2

(Note: S: Staggered pattern, U: Uniform pattern)

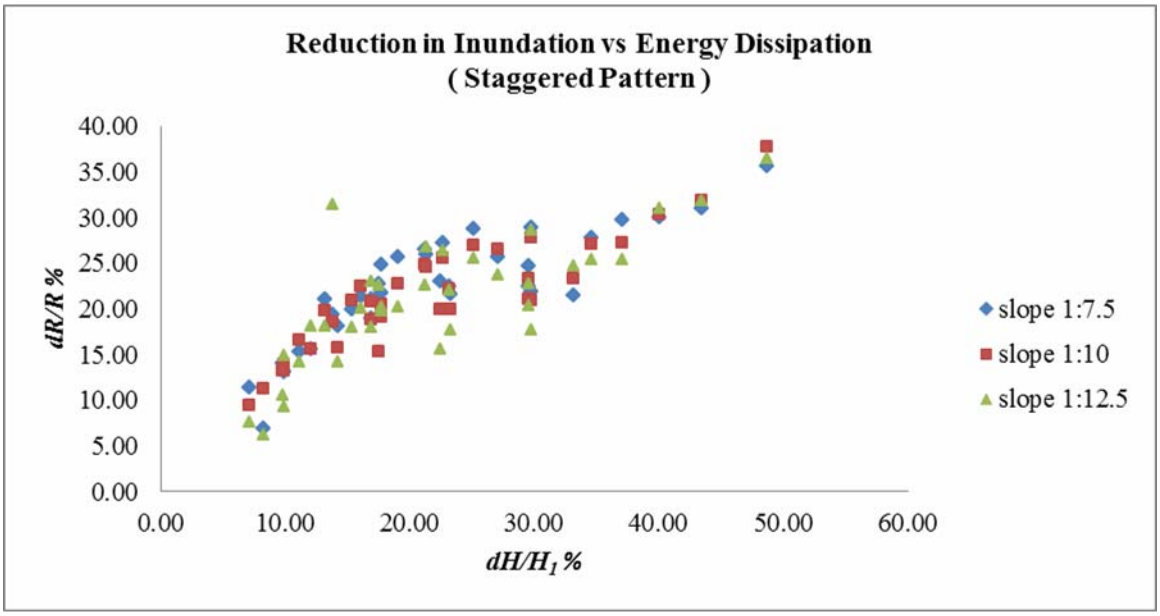

Figure 4(a): *Levels of Impact mitigation and Energy dissipation*

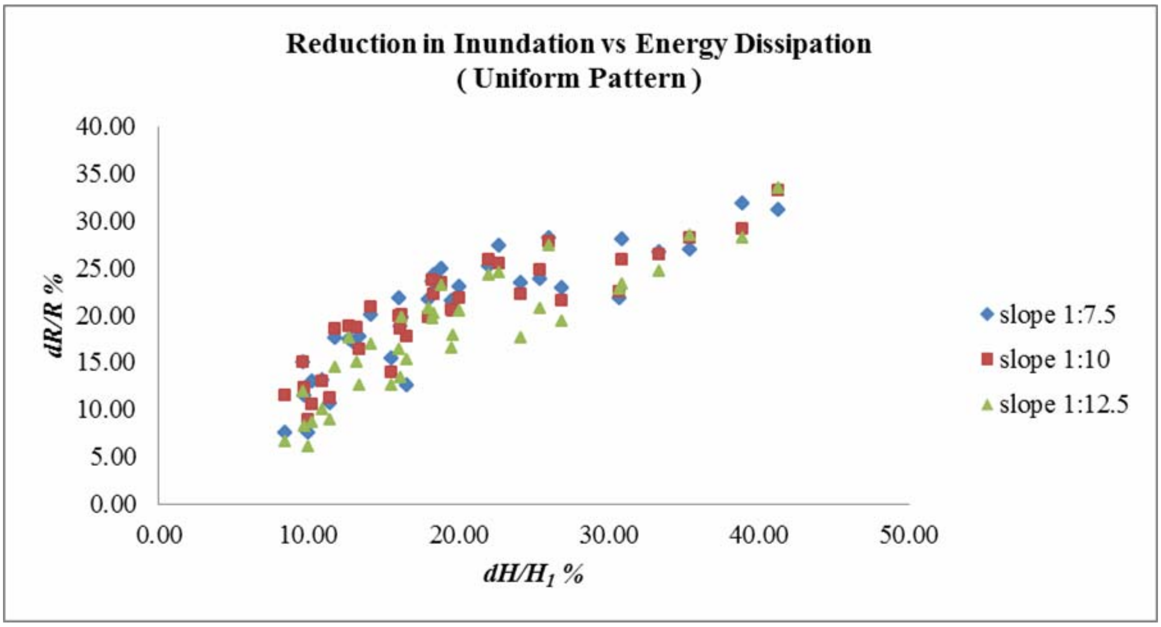

Figure 4(b): *Levels of Impact mitigation and Energy dissipation*

As indicated in Table 2, with significant energy dissipation levels reaching 48 % in parallel with reduction levels of inundation extent reaching 38 %, it is evident that vegetation is effective in mitigating adverse impacts of tsunami inundation. The dependence of reduction of inundation extent on energy dissipation by coastal vegetation is clearly evident in Figure 4(a) and Figure 4(b).

Relative influence of the various characteristics of the vegetation can be assessed by comparing the results of relevant model tests. The comparison of tests (3,12,21 and 30), (1,2 and 3) and (3, 6 and 9) reveals the influence of thickness of the vegetation belt, size of individual plants and plant density on energy dissipation as shown in Figure 5(a).

Two grid patterns of vegetation, staggered and uniform have been considered in testing in order to represent the irregular pattern of naturally grown vegetation and regular pattern in plantations. The Figure 5(b) reveals that the higher levels of energy dissipation occurred with staggered pattern of vegetation, possibly due to high levels of flow interception than uniform pattern, indicating the significance of natural coastal vegetation belts.

The influence of vegetation characteristics in reducing inundation distance was also considered and the approximately same order of influence was observed as in energy dissipation. This further reveals the dependence of reduction in inundation distance on energy dissipation.

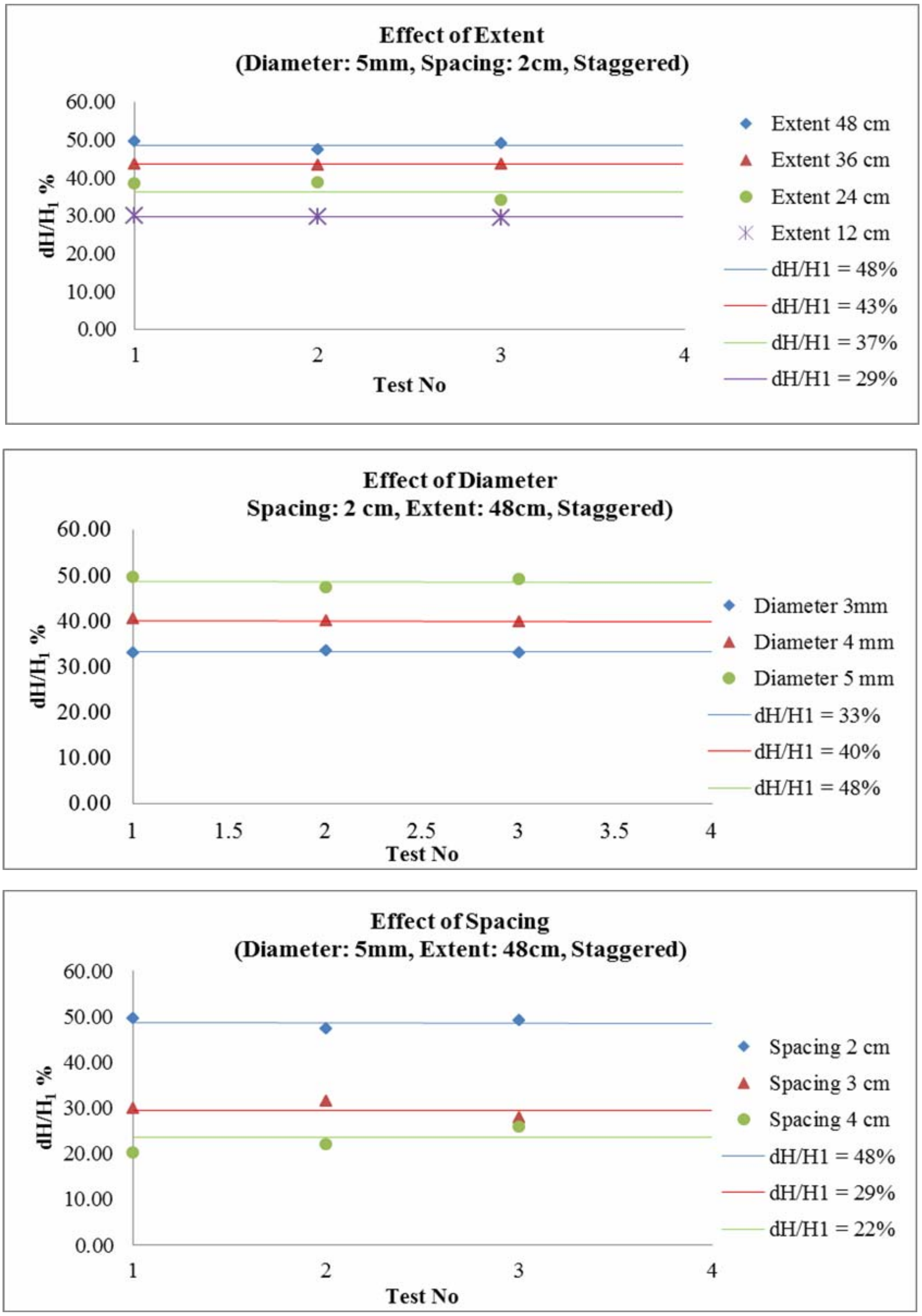

Figure 5(a): *Relative Influence of various characteristics (Extent, Size and Density) of vegetation in Energy dissipation*

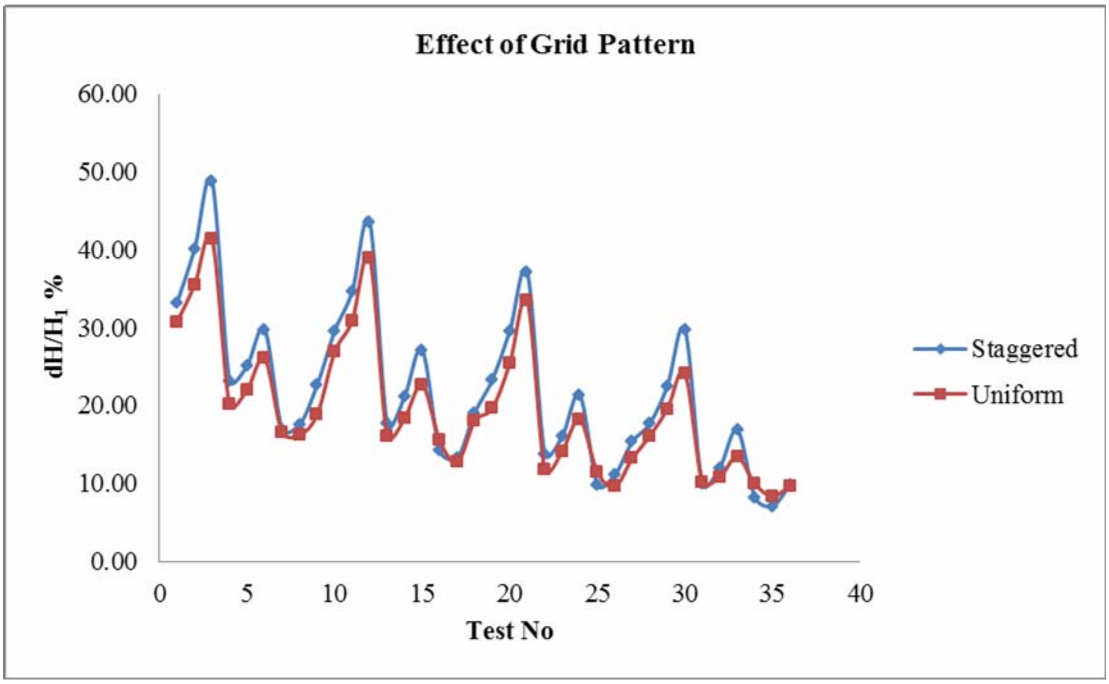

Figure 5(a): *Relative Influence of various characteristics (Pattern) of vegetation in Energy dissipation*

6 Concluding Remarks

The results of an investigation carried out by using small scale physical models under both steady flow conditions and unsteady flow conditions to assess the effectiveness of coastal green belts in mitigating impact and energy dissipation of tsunami overland flow are presented. Significant levels of energy dissipation and reduction in inundation extent were observed through experimental studies and relative influence of vegetation characteristics in impact mitigation such as extent, plant size spacing/density and distribution pattern were identified by the study.

In spite of the restrictions imposed by the small scale used in the tests, as the analysis is based on assessing the relative influence of various characteristics of vegetation, the results are expected to provide useful guidance on the effective use of coastal green belts as a possible tsunami impact mitigation measure.

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