Coastal Flooding and Protection from Bio-Shields

A. H. R. Ratnasooriya and S. P. Samarawickrama

Abstract: In addition to the flooding associated with heavy rainfall, coastal flooding can also be caused by storm surges, tidal waves and tsunamis. The potential of such hazards to cause severe damages in coastal regions and the protection offered by bio shields-coral reefs, coastal sand dunes and vegetation was evident in the aftermath of the Indian Ocean Tsunami in 2004. In this investigation, attention was focussed on the mitigation of tsunami induced flooding by coastal vegetation and results of small scale physical model studies carried out to assess the energy dissipation characteristics of selected forms of vegetation and the reduction in the extent of inundation due to the presence of vegetation are presented. The results indicate significant levels of energy dissipation and reduction in the extent of inundation. A vegetation may be characterized by the type of plants, density (spacing), extent, pattern and location and the relative influence of these characteristics on energy dissipation and reduction of inundation are also presented.

Keywords: Tsunami, Hazards, Mitigation, Bio Shields, Coastal, Vegetation

1. Introduction

Water related hazards, mainly in the form of flooding, are perhaps the most frequent natural hazards in the country. With increasing population, denser occupation of flood prone areas and inappropriate land use patterns, the impacts due to such hazards could become more devastating. In coastal regions, flooding can be caused by several phenomena. In addition to the flooding associated with heavy rainfall, coastal flooding can also be caused by storm surges, tidal waves and tsunamis. Although such events have relatively been rare in Sri Lanka and the impacts are restricted to a relatively narrow strip of coastline, they have the potential to cause severe damages in coastal regions of the country which are densely populated, as was evident in the aftermath of the Indian Ocean Tsunami (IOT) in 2004. In this investigation, attention was focussed on the impact mitigation of coastal flooding caused by tsunamis.

2. Tsunami Hazards and Coastal Flooding in Sri Lanka

Sri Lanka had earlier been considered as a country free from major natural disasters such as tsunamis, but the IOT in 2004 and subsequent tsunami alerts in March 2005 and September 2007, together with historical records of possible tsunami events in the past have highlighted the vulnerability of the country to such hazards.

The majority of tsunamis, approximately 85%, are caused by undersea earthquakes and, in view of the geographical location of Sri Lanka relative to the undersea earthquake prone regions of the world, it is evident that the country is exposed to the potential tsunamis generated along the Sunda Trench located to the east, off the coasts of the Indonesian islands of Java and Sumatra as well as to the tsunamis generated at the Makran fault, located to the northwest, off the coast of Pakistan shown in Fig. 1.

The IOT caused widespread damage in coastal areas of the country with more than two thirds of the 1600 km long coastline in the northern, eastern, southern as well as relatively sheltered western regions undergoing inundation. With the local near shore wave height, topography and the resistance offered to the overland flow, the inundation distance, depth and the associated damage caused by the coastal flooding varied significantly. The extent of flooding in northern and eastern areas reached 2-3 km inland and, in southern and western areas, reached 500 m in certain locations.

Eng. A. H. R. Ratnasooriya, B.Sc.Eng.(Hons) (Moratuwa), AMIE(Sri Lanka), M.Phil (Moratuwa), Senior Lecturer, Department of Civil Engineering, University of Moratuwa, Sri Lanka.

Eng. (Prof.) S. P. Samarawickrama, B.Sc.Eng.(Hons.) (Moratuwa), C. Eng., MIE(Sri Lanka) PhD(London), DIC, Professor, Department of Civil Engineering, University of Moratuwa, Sri Lanka.

Figure 1 - Sunda Trench and Makran Fault

3. Impact Mitigation by Bio-Shields

Subsequent to the IOT disaster, the protection offered by various natural features: sand dunes, coral reefs and coastal vegetation has become evident in many countries affected and the role of these bio-shields in mitigating tsunami impacts has been recognized [1], [3], [4]. The protection offered by sand dunes in the southern regions of the country was evident during the IOT in 2004. Similar to tsunami dykes, sand dunes were effective in intercepting the oncoming tsunami and protecting the sheltered areas whereas the adjacent areas exposed due to the absence of sand dunes, or sometimes due to the artificial removal of sand dunes, suffered severe destruction. Coral reefs are effective in dissipating wave energy and coastal erosion problems, probably due to coral mining are evident in south western regions of Sri Lanka. The severe tsunami damage suffered by these areas has also highlighted the possible adverse impacts of coral mining in the region. The forces resisting the tsunami induced overland flow due to vegetation are effective in dissipating the energy of flow leading to reduction of the extent of inundation [2].

In view of the infrequent nature of tsunamis affecting Sri Lanka and the widespread extent of the coastal area inundated in 2004, it is evident that the development and utilization of bio-shields would be effective in developing appropriate tsunami impact mitigation measures for the country. Such methods would also have the advantages of being cost effective, environmentally friendly and sustainable.

4. Flow through Vegetation and Energy Dissipation

From a hydraulic point of view, the flow through vegetation can be considered as flow around a group of non-streamlined solid bodies. In fluid flow around a solid body, the energy dissipation takes place due to drag and inertia resistance offered and, in tsunami induced overland flow caused by long waves of large periods up to even one hour or more, the accelerations are smaller and the inertia resistance can be neglected [3,4] in comparison to the drag resistance. It can thus be considered that the energy dissipation of flow through vegetation is predominantly caused by drag resistance F which can be expressed as,

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

where ρ = Density of fluid
 C_D = Drag coefficient
 A = Projected area of solid body
 U = Steady velocity of the flow

For non-streamlined bodies, the effect of surface roughness is negligible and the drag coefficient depends on the shape of the body and the characteristics of the wake formed due to separation of flow around the solid body. Distinct shapes of the wake have been identified for different ranges of Reynolds Number Re , which, for a cylindrical body can be defined as,

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

where D = Diameter
 ν = Coefficient of kinematic viscosity of fluid

In flow around a group of solid bodies, the wake produced by a body upstream is intercepted and disturbed by bodies located downstream, the drag resistance is expected to be affected by the presence of such bodies. The total resistance offered by a group of solid bodies would thus likely to be influenced by the number of bodies and the way such bodies are distributed to form the group.

A vegetation can be characterized by the characteristics of individual plants (i.e. size and shape) as well as the overall characteristics

of the vegetation, namely, spacing (density), extent and pattern of vegetation. The factors affecting the drag resistance can thus be related to the characteristics describing the vegetation as indicated in Fig. 2.

Figure 2 - Drag Resistance and Vegetation Characteristics

5. Steady Flow Tests

In order to determine energy dissipation characteristics, small scale (approximately 1:100) physical model studies were conducted in a hydraulic flume of length 10 m, width 30 cm and depth 30 cm. The vegetation was represented by small scale geometrically similar configurations and water was allowed to flow under steady conditions as shown in Fig. 3(a) and Fig. 3(b).

Figure 3(a) - Experimental Set-Up: Steady Flow Tests

Figure 3(b) - Experimental Set-Up: Steady Flow Tests

The total head of flow H can be expressed in terms of the depth y and velocity of flow v as,

$$H = y + \frac{v^2}{2g} \dots\dots\dots (3)$$

As

$$V = \frac{Q}{By} \dots\dots\dots (4)$$

where Q = Rate of flow
 B = Width of the flume

$$H = y + \frac{Q^2}{2gB^2} \dots\dots\dots (5)$$

Neglecting frictional head loss and the bed slope over the short length of vegetation, the head loss due to the presence of vegetation dH can be expressed as:

$$dH = (y_1 - y_2) + \frac{Q^2}{2gB^2} \left[\frac{1}{y_1^2} - \frac{1}{y_2^2} \right] \dots\dots\dots (6)$$

where the subscripts 1 and 2 indicate upstream and downstream flow conditions as shown in Figure 3(b) and can be determined from discharge and depth measurements. The downstream depth y_2 was measured at the section representing the minimum depth of flow to ensure the validity of Equation (3).

The vegetation was represented by geometrically similar small scale model configurations. Based on field studies three distinct components of a plant structure, aerial roots, stem and branch/leaf structure, offering varying degrees of resistance have been identified [2]. These are shown in Figure 4. Considering such components together with depth of inundation, 4 categories of vegetation have been identified as indicated in Table 1.

Table 1 - Categories of Vegetation

Category	Inundation		
	Aerial Root System	Stem	Branch/ Leaf structure
I	No	Yes	No
II	No	Yes	Yes
III	Yes	Yes	No
IV	Yes	Yes	Yes

Figure 4 - Components of a Plant Structure

In this investigation, physical model studies were carried out for category I plants, which were represented by nails of diameter 4 mm. The values of parameters in physical models of vegetation configurations are shown in Table 2.

Table 2-Physical Model Parameters: Steady and Unsteady Flow Tests

Test	c_1 (cm)	b_1 (cm)	c_2 (cm)	b_2 (cm)	Spacing (cm)	Pattern U/S
1	0	15	0	0	2	U
2	0	15	0	0	2	S
3	0	30	0	0	2	U
4	0	30	0	0	2	S
5	0	15	10	15	2	U
6	0	15	10	15	2	S
7	0	15	0	0	2	U
8	15	15	0	0	2	S
9	15	30	0	0	2	U
10	15	30	0	0	2	S
11	0	15	0	0	3	U
12	0	15	0	0	3	S
13	0	30	0	0	3	U
14	0	30	0	0	3	S
15	0	15	10	15	3	U
16	0	15	10	15	3	S
17	0	15	0	0	4	U
18	0	15	0	0	4	S
19	0	30	0	0	4	U
20	0	30	0	0	4	S
21	0	15	10	15	4	U
22	0	15	10	15	4	S

(Note: c_1 : For Unsteady Flow Tests only)

For each configuration, measurements were taken for a number of sub critical flow depths and discharges.

6. Unsteady Flow Tests

Ratnasooriya et al [2] conducted unsteady flow tests to investigate the tsunami impact mitigation characteristics of coastal vegetation. These were conducted in the same hydraulic flume in which the steady flow tests were conducted in this investigation. Unsteady flow

conditions in the flume were generated by suddenly releasing water contained in a tank in the flume by the opening of a gate simulating a 'dam break' and water was allowed to run over a sloping surface. Coastal vegetation was represented by the same small scale model configurations used in the steady flow tests. The other parameters in the tests are shown in Table 3. The experimental set-up is shown in Fig. 5(a) and Fig. 5(b).

Table 3 - Physical Model Parameters: Unsteady Flow Tests

H (cm)	L (cm)	a (cm)	θ^0
25			4.5
20	50	250	8.9
15			13.6

Figure 5(a) - Experimental Set-Up: Unsteady Flow Tests

Figure 5(b) - Experimental Set-Up: Unsteady Flow Tests

The effectiveness of vegetation in mitigating tsunami impacts was assessed by the % reduction in inundation distance (R) over the sloping surface due to the presence of vegetation. The % reduction dR/R_0 was computed by Equation (7).

$$dR/R_0 = (R_0 - R)/R_0 \dots\dots\dots (7)$$

where R_0 is the inundation distance without the presence of vegetation.

7 Results and Analysis

In the steady flow tests, the % head loss dH/H_1 , where H_1 is the total head of incoming flow, was determined for the flow depths and discharges considered for each geometric configuration. The average value of the % head loss was used for comparative purposes to assess the energy dissipation characteristics of vegetation.

Similarly, in unsteady flow tests, the average value of dR/R_0 for each geometric configuration has been used to assess the tsunami impact mitigation characteristics of vegetation.

The average values of dH/H_1 and dR/R_0 for each geometric configuration of vegetation tested are summarized in Table 4.

Table 4 -Results: Steady and Unsteady Flow Tests

Test	dH/H_1 (%)	dR/R_0 (%)
1	13.6	26.2
2	18.7	32.2
3	22.2	32.9
4	28.1	36.3
5	22.6	35.0
6	27.4	37.3
7	-----	20.7
8	-----	21.4
9	-----	29.9
10	-----	28.4
11	7.3	14.5
12	9.4	18.8
13	11.3	22.9
14	14.4	27.3
15	12.9	21.8
16	14.5	29.0
17	3.8	8.5
18	4.9	13.5
19	9.0	17.0
20	9.3	20.1
21	9.2	14.0
22	9.6	22.0

Significant levels of energy dissipation (nearly up to 30 %) and reduction in the extent of inundation (nearly up to 40 %) are shown in Table 4 indicating the effectiveness of vegetation in mitigating coastal inundation. The dependence of the level of impact mitigation on the level of energy dissipation is clearly evident in Fig. 6.

The relative influence of the characteristics describing a vegetation-spacing (density), extent, pattern and the location relative to the

coastline on energy dissipation and impact mitigation could be assessed by the comparison of relevant test results indicated in Table 4.

Figure 6 - Levels of Impact Mitigation and Energy Dissipation

The tests were conducted for the spacings of 2 cm, 3 cm and 4 cm between individual plants of the vegetation. The comparison of the results of the tests (1,11 and 17), (2, 12 and 18), (3, 13 and 19) and (4, 14 and 20) reveals the most significant influence of the density of vegetation on energy dissipation and impact mitigation.

As many of the coastal areas in the country are densely populated, only a limited extent of land may be available for the possible creation of coastal green belts. Two limited extents of vegetation, 15 cm and 30 cm, were used in the tests. The influence of the extent of vegetation is assessed by the comparison of the results of the tests (1 and 3), (2 and 4), (11 and 13), (12 and 14), (17 and 19) and (18 and 20). Although the levels of energy dissipation and impact mitigation increase with the extent as anticipated, a comparison with the corresponding effect of density reveals the significantly higher influence of the density of a vegetation on impact mitigation. The creation of a coastal green belt may be further restricted due to the road network with long stretches located parallel and close to the coastline. In order to investigate such restrictions, vegetation configurations with a gap in the middle were considered in the testing program. The effect of such a gap of width 10 cm can be assessed by the comparison of the results of the tests (3 and 5), (4 and 6), (13 and 15), (14 and 16), (19 and 20) and (21 and 22). Although such a comparison reveals the that the same extent of vegetation with a gap would be as effective as the extent without such a gap, conclusions need to be

based on further testing due to the limited range of parameters considered in the tests conducted.

The pattern of distribution of individual plants in a vegetation could be irregular as in a naturally grown vegetation or regular as in a plantation. Two grid patterns-uniform (U) and staggered (S)-were thus considered in the tests. The higher levels of energy dissipation and impact mitigation, possibly due to higher levels of flow interception, by the staggered pattern of vegetation are evident from the comparison of the results of the tests (1 and 2), (3 and 4), (11 and 12), (13 and 14), (17 and 18) and (19 and 20).

The influence of the location of vegetation could be assessed by the comparison of the results of the tests (1 and 7), (2 and 8), (3 and 9) and (4 and 10) which indicates the higher levels of effectiveness of vegetation located at the coastline.

8 Concluding Remarks

The results of an investigation carried out to assess the effectiveness in utilizing coastal vegetation for the mitigation of coastal flooding induced by tsunami hazards are presented. Small scale physical model tests under steady flow conditions were conducted to assess the energy losses of flow through vegetation and the results were used together with the results of a physical model study conducted under unsteady flow conditions to identify the energy dissipation and impact mitigation characteristics of a coastal vegetation. Significant energy dissipation and inundation reduction levels were obtained in the experimental studies indicating the effectiveness of coastal green belts in tsunami impact mitigation. The relative influences of the characteristics describing a vegetation-density, extent, pattern and location of vegetation on energy dissipation and impact mitigation were also identified by the study.

As the results were used for the interpretation of the relative influence of the presence of vegetation as opposed to extrapolation to quantify prototype conditions, in spite of the small scale used, the physical model results can be considered to be reasonably representative of the prototype behaviour and expected to provide useful guidance on the

effective utilization of coastal green belts as a possible tsunami impact mitigation measure.

References

1. Kandasamy, K. and Narayansamy, R., Coastal Mangrove Forests Mitigated Tsunami, *Estuarine, Coastal and Shelf Science*, 2005, 65(3), pp. 601-606.
2. Ratnasooriya, A. H. R., Samarawickrama, S. P., Hettiarachchi, S. S. L. Bandara R. P. S. S. and Tanaka, N., "Mitigation of Tsunami Inundation by Coastal Vegetation", "Engineer", *Journal of the Institution of Engineers, Sri Lanka*, October 2008.
3. Tanaka, N., Sasaki, Y., Mowjood, M. I. M., Jinadasa, K. B. S. N. and Takemura, T., Effective Coastal Vegetation Species and Structures with Landform, Sand Dune and Lagoon for Tsunami Protection at the Indian Ocean Tsunami, 15th APD-IAHR Congress, 2006, pp. 1279-1285.
4. Tanaka, N., Sasaki, Y., Mowjood, M. I. M. and Jinadasa, K. B. S. N., Coastal Vegetation Structures and their Functions in Tsunami Protection: Experience of the Recent Indian Ocean Tsunami, *Landscape and Ecological engineering*, 3, 2007, pp. 33-4.

Acknowledgement

The authors wish to thank the Senate Research Committee of the University of Moratuwa, for providing assistance to conduct this study. The testing program was conducted at the Hydraulic Engineering Laboratory in the Department of Civil Engineering of the University of Moratuwa and the support extended by the laboratory staff is acknowledged.