Ocean Engineering 141 (2017) 308–325

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Undular hydraulic jump formation and energy loss in a flow through emergent vegetation of varying thickness and density

Ghufran Ahmed Pasha[a], Norio Tanaka[a,b,*]

[a] Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan
[b] International Institute for Resilient Society, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan

ARTICLE INFO

Keywords:
Tsunami
Vegetation
Backwater rise
Undular hydraulic jump
Energy loss
Drag coefficient

ABSTRACT

Floods resulting from extreme events like tsunamis may inundate widespread inland areas, but vegetation can act as a natural buffer zone to reduce the inundation area and dissipate the energy of flowing water. This paper summarizes a series of laboratory experiments in which the energy loss through emergent vegetation in a steady subcritical flow was investigated. The energy loss was determined against vegetation of variable thickness (dn, where d = diameter of cylinder, n = number of cylinders in a stream-wise direction per unit of cross-stream width), density (G/d, where G = spacing of each cylinder in cross-stream direction, d = diameter of cylinder), and initial Froude number. On the upstream side of vegetation, the backwater rise increased by increasing both vegetation thickness and density. Contrarily, on the downstream side a breaking undular jump with a lateral shock wave was observed for a dense vegetation arrangement (G/d = 0.25), whereas a non-breaking undular jump with and without air bubbles was identified for intermediate (G/d = 1.09) and sparse (G/d = 2.13) vegetation conditions, respectively. Under these conditions, the maximum energy reduction due to a jump reached 6.4% for dense vegetation, and was reduced to 1.7% and 1.4% for intermediate and sparse vegetations, respectively. Hence, denser vegetation offers larger resistance, thus causes significant energy loss.

1. Introduction

Various researchers have worked in recent years to derive the best possible method for tsunami mitigation (Nateghi et al., 2016; Rahman et al., 2017; Tanaka, 2012; Thuy et al., 2012). Both artificial (hard solutions) and natural (soft solutions) methods can be implemented to dissipate the energy carried by the huge currents of a tsunami. Artificial methods include construction of sea walls and embankments, installing tsunami gates, and putting up breakwater structures. These methods can prove costly for developing countries because they require a huge capital investment (Tanaka, 2009). Further, the money will be wasted if a large tsunami arrives exceeding the designed capacity of the artificial structure, thus causing disastrous damage to people, infrastructures (Suppasri et al., 2012; Fraser et al., 2013; Ishigaki et al., 2013), and even coastal forests (Tanaka et al., 2013). Currently, natural methods such as coastal forests are widely considered to be an effective measure to mitigate tsunami damage from both economic and environmental points of view (Kathiresan and Rajendran, 2005; Osti et al., 2009; Tanaka, 2009; Yanagisawa et al., 2009, 2010).

Based on previous work (Shuto, 1987; Tanaka et al., 2007), the roles of coastal vegetation in tsunami mitigation include trapping, energy dissipation, a soft landing place, and an escape route. The effectiveness of a coastal forest as protection depends upon various factors, including tree density (Harada and Kawata, 2005; Irtem et al., 2009; Tanaka et al., 2011), deficiencies in coastal forests such as open gaps (Mascarenhas and Jayakumar, 2008; Thuy et al., 2009), the breaking moment of trees (Tanaka et al., 2009), and magnitude of the tsunami (Tanaka, 2009). Since the 1998 Papua New Guinea tsunami (Dengler and Preuss, 2003), many researchers have investigated the effects of coastal vegetation on tsunami mitigation. Hiraishi and Harada (2003) did field investigations after the Papua New Guinea tsunami and proposed a green belt of mango or coconut trees to reduce the tsunami force. Previous post-tsunami surveys have also shown that coastal trees help reduce the damaging effects of natural disasters (Danielsen et al., 2005; Kathiresan and Rajendran, 2005; Tanaka et al., 2007; Mascarenhas and Jayakumar, 2008). To utilize the tsunami mitigation function of a coastal forest, field plantation has also been done along the coast of southern Asian countries (Tanaka, 2009; Tanaka et al., 2011).

Hydraulic resistance and reflection of water by trees can reduce the energy of flowing water, inundation depth, inundation area, and hydraulic force behind the vegetation. The force of the water passing through the vegetation becomes weaker, which minimizes the damage

* Corresponding author at: International Institute for Resilient Society, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338–8570, Japan.
E-mail address: tanaka01@mail.saitama-u.ac.jp (N. Tanaka).

http://dx.doi.org/10.1016/j.oceaneng.2017.06.049
Received 29 June 2016; Received in revised form 10 May 2017; Accepted 19 June 2017

behind the vegetation. Iimura and Tanaka (2012) investigated the effects of vegetation density both experimentally and analytically and confirmed that both the level and velocity of the water behind the vegetation are reduced considerably by increasing the density of vegetation. Denser vegetation causes increased water reflection and resistance because the water surface slope in the vegetation region is increased. Later, Iimura and Tanaka (2013) studied the effects of aspect ratio on tsunami mitigation using numerical simulations and found that the effect of the collision of an inundating current behind a forest is large if the aspect ratio is between 1 and 4. An increase in forest width can reduce not only inundation depth but also the current and hydraulic force behind a coastal forest (Harada and Imamura, 2005). Moreover, a few studies changed the tree density distribution in a forest and investigated the energy reductions behind the forest (Thuy et al., 2009; Iimura and Tanaka, 2012). However, no one has reported the flow structure and patterns downstream of a forest and possible energy reduction due to the formation of a hydraulic jump.

In open channels, the transition from supercritical to subcritical flow is called a hydraulic jump. The different kinds of hydraulic jumps were described by Chow (1959). A jump is characterized by the development of large scale turbulence, surface waves, energy dissipation, and air entrainment. For a Froude number slightly above unity, the hydraulic jump is considered a smooth rise of the free surface, followed by a train of stationary free-surface undulations known as an undular hydraulic jump (Chanson, 2009). Undular jumps are often observed downstream of low drop-structures or in a transitional region from steep to mildly sloping channels (Ohtsu et al., 2003). An undular hydraulic jump may also occur behind ships travelling in canals and shallow waters (Haslewood, 1985). Various researchers have done experimental studies in an open channel to study the flow of an undular hydraulic jump by a sluice gate (Chanson and Montes, 1995; Ohtsu et al., 2001, 2003), but the development of an undular hydraulic jump formed in the wake of a coastal forest, especially during a tsunami event, has never been reported. However, a few undular flow patterns were observed in a forest downstream during the 2011 Japan tsunami near a bank of the Yuriage area (photo 16, Tokida and Tanimoto, 2014). The arrangement of trees in a forest can transform the flow into a supercritical flow that results in the occurrence of a hydraulic jump. To clarify the energy loss mechanism, not only by drag force but also the downstream flow pattern change, flume experiments were conducted to determine the amount of energy loss through emergent vegetation of variable thicknesses, changing density, and flow conditions. Different flow patterns of undular hydraulic jumps were also identified. This study will help in selecting an optimal forest width in relation to different flow conditions and vegetation arrangements.

2. Materials and methods

2.1. Experimental procedure and flume characteristics

2.1.1. Flume characteristics

Laboratory experiments with nine different conditions (Table 1) were conducted in a glass-sided water flume (constant bed slope 1/500) that is 5 m in length, 0.7 m in width, and 0.5 m in height at Saitama University. Fig. 1a shows a schematic figure of the water channel. In the experimental channel, the ground conditions and tsunami characteristics implicated were not specific to any location but were considered in general. Based on video analysis, Nandasena et al. (2012) estimated that the maximum Froude number ($Fr = V/(gh)^{0.5}$, where V = depth-averaged velocity (m/s), g = gravitational acceleration (m/s^2), and h = water depth (m)) was around 1.5 at the time the tsunami reached the Misawa and Hachinohe shores in Japan, whilst the Froude number was about 1.14–1.4 at the wave front 1 km inland from the coast of the Sendai Plain which had no tsunami mitigation structure such as a coastal forest. At many locations inundated by the tsunami, the tsunami's flow was subcritical and had a Froude number between 0.7 and 1 (Spiske et al., 2010). For the Great East Japan tsunami, Tanaka et al. (2013) estimated the Froude number as 0.9–0.6 at 500–550 m distance from the shoreline, and a simulation by Tanaka et al. (2014) estimated the Froude number to decrease from 1.6 near the shoreline to 0.6 around 550 m from the shoreline in the Sendai Plain. In the current study, to set the flow conditions, Froude similarity was applied to set the model scale of the physical experiment. This study defined the initial Froude number (Fr_o) when the reference velocity and water depth were used without a vegetation model. For creating subcritical conditions of an inundating tsunami, the water depths (model without vegetation) selected in the experiment were 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5 and 7 cm, setting the initial Froude number approximately equal to 0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, and 0.73, respectively. As a first step, a slightly lower range of initial Froude numbers was selected due to the restricted length of the channel. This is because flow with a higher Froude number increases the length of the hydraulic jump. Also, the behavior of an undular hydraulic jump downstream of vegetation is investigated better against a low initial Froude number. As discussed in the previous studies (Tanaka et al., 2013; Pasha and Tanaka, 2016), it is better to set a coastal forest inland, where it is expected to trap tsunami-borne floating debris. From that point of view, the experimental condition is set in the lower range of Froude numbers in the post-tsunami research (Spiske et al., 2010; Tanaka et al., 2013, 2014).

Table 1
Experimental conditions.

Case No.	Initial Froude number 'Fr_o'	Vegetation density 'G/d'	D (cm)	W (cm)	Vegetation thickness 'dn' (No. cm)	Vegetation type
1	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	0.25	1	3.88	179.21	Dense
2	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	1.09	1.67	10.55	174.72	Intermediate
3	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	2.13	2.5	24.27	179.36	Sparse
4	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	0.25	1	8.23	380.13	Dense
5	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	1.09	1.67	23.60	390.85	Intermediate
6	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	2.13	2.5	52.48	387.83	Sparse
7	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	0.25	1	12.58	581.05	Dense
8	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	1.09	1.67	35.2	582.96	Intermediate
9	0.57, 0.62, 0.65, 0.66, 0.68, 0.69, 0.70, 0.71, 0.73	2.13	2.5	78.52	580.27	Sparse