Ocean Engineering 169 (2018) 87–98

Contents lists available at ScienceDirect

Ocean Engineering

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

Modeling of solitary breaking wave force absorption by coastal trees

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ARTICLE INFO

Keywords:
Coastal green belt
Solitary wave
Momentum absorption
Wave breaking

ABSTRACT

Tall vegetation in the form of green belt along the shorelines is considered an environmentally friendly and cost-effective strategy against large coastal wave damages. Comprehensive experiments were carried out to determine the effects of green belt on attenuation of solitary wave height and force. A novel technique based on momentum approach was used to measure direct wave force absorbed by simulated green belt. Using artificial trees with different densities, the simulated coastal forest was exposed to the breaking waves with different heights. The green belt was simulated on a movable section of a flume. The movable section with 1-m length was mounted on frictionless supports at the middle of the flume to allow direct transfer of the absorbed horizontal wave force to the load cell between moveable and stationary sections of the flume. Instantaneous wave height was measured using recorded video and pressure transducers in five points before and after the vegetation section. Results indicated a considerable effect of green belt on the reduction of the wave force and inundation depth. For example, inundation depth decreases 14%, 18%, and 29% in average for the coastal vegetation density of 30%, 50%, and 100%, respectively.

1. Introduction

Coastal areas are of great importance because of economic development, as well as international and even political communications view. Furthermore, they are one of the common human activity zones. About two-third of world's population lives on or near coasts, and many others visit the coast periodically (Sorensen, 2006). This issue brings strong pressure for shore development for housing and recreational facilities and coast protection from storms and overflowing waves. Waves are the dominant phenomenon in shaping the coasts geometry condition, and also have a major impact on the design of ports, waterways, and coastal structures. A large amount of the world's commerce is carried by ships through the ports on the coasts, which requires stabilization, maintenance, and protection of coastal navigation channels. There are several ways to protect the coasts which are generally based on structural and non-structural methods. Traditional ways of protecting the coastline include construction of all types of quays, breakwaters and other protective structures such as sea walls and groins in order to dissipate energy and reflect waves. During different periods, due to the intrinsic advantages resulting from the use of natural protection methods, the approaches are altering from structural reinforcement to natural supporting of the coastline. At the moment, coastal vegetation, which fits in the current conservation trends, is considered as a form of biological control, playing a major role in the development and protection of the ecosystems. Green belt is composed of the tropical trees with sufficient stability against tsunami force and it may grow by the residential vegetation in the coastal areas (Hirashi and Harada, 2003). Coastal vegetation not only reduces tsunami overflow development due to the increase of roughness and resistance but also has further advantages such as environmental compatibility and economic efficiency. In recent decades, there has been a growing interest in the study of coastal forest effect on the protection of see coast, rivers, estuaries and bays. This is a new approach in solving hydraulic and coastal engineering problems based on the ecological balance of the environment.

Owing to the resistance of vegetation against flow, water wave's development through submerged and non-submerged vegetation was accompanied by energy loss and wave height reduction (Dalrymple et al., 1984). Wave attenuation by coastal forest is a function of vegetation characteristics such as geometry and structure, submergence ratio, density, stiffness, local arrangement, as well as wave conditions such as incident wave height, period, and direction. Interaction of wave and coastal vegetation causes temporal variations of waves and physical changes of trees such as bending, breaking or uprooting.

Despite many dependencies between wave attenuation and the large diversity of coastal plants, the variations of wave attenuation by coastal vegetation is significant (Mendez and Losada, 2004). Irtem et al. (2009) carried out an experimental study to determine the effects of a coastal

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https://doi.org/10.1016/j.oceaneng.2018.09.021
Received 23 October 2017; Received in revised form 6 September 2018; Accepted 10 September 2018

forest on tsunami run-up heights. They concluded that the maximum reduction of run-up height was 45% relative to the case without coastal forest. This occurred when the trees were placed in a dense rectilinear layout and close to the still water level. As demonstrated in Dean and Bender (2006), using linear theory of waves in shallow water condition, transmitted momentum resulting from the wave breaking process is mitigated two to three times more in the presence of vegetation in comparison with the non-vegetated condition. Hirashi and Harada (2003) studied the performance of coastal green belt against tsunami waves in Indonesia and New Guinea in the South Pacific Ocean by a series of experiments, and by gathering actual data from the occurred tsunami in the mentioned region, began to analyze the amount of vegetation efficiency in reduction of the waves' destructive effects. Comparing with other structures such as breakwaters, they elucidated the superiority of the proposed option from both aspects of cost and force reduction. They also expressed that the amount of wave attenuation depends on the vegetation density. This amount of porosity in a particular surface denotes the performance of vegetation, which can be investigated by the drag coefficient as a representative of flow resistance.

The green belt should be built between the coastline and the residential area, which includes different types of tropical trees such as coconut, palm, mango, and mangrove. Mangrove has a complex aerial root system and dense leaves which are suitable for long and tidal wave height reduction (Harada and Imamura, 2000). There is a general idea that wetlands, which are often considered as a transition area between water and land and include submerged and non-submerged vegetation, can operate as a buffer and remarkably reduce the storm and wave forces before being developed on the coasts (Anderson et al., 2011). While earlier studies tend to quantify wave dissipation among vegetation (Knutson et al., 1982; Wayne, 1976), new investigations focus on comparing with and without vegetation areas in order to emphasize the importance of preserving and creating wetlands for coastal protection (Quartel et al., 2007; Mazda et al., 2006; Cooper, 2005; Mooler and Spencer, 2002; Mooler et al., 1999). The studies of Mascarenhas and Jayakumar (2008) on the Tamil Nadu coast (South East of Indian Peninsula) indicated the large effect of Casuarinas (Australian pine), coconut, and palm trees on coastal wave attenuation. A total of five villages including two on the coast and three behind mangroves in southeastern India were studied. It was found that villages on the coast were totally damaged, while areas shielded by mangroves located at the same distance from the coast experienced no destruction (Danielsen et al., 2005). The significant role of coastal trees to reduce wave inundation distance and run-up during the ingress of the great Indian Ocean tsunami of 2004 was reported by Kathiresan and Rajendran (2005).

In general, researches on the interaction of solitary sea waves and coastal fences are mostly limited to the mathematical models, though some physical models are also used to understand the behavior of green belt and calibration of mathematical models. For the physical modeling of coastal wave attack, individual rigid stems or a group of slender cylinders with constant height and diameter are normally used to simulate the green belt effect (Meijer and Van Velzen, 1999). Based on a similar understanding of the vegetation flexibility and deflection as in Fathi-Moghadam (1996), Kutija and Hong (1996) coupled a numerical model with a vegetation bending model to simulate coastal green belt effects. Numerical and experimental studies have been performed by Erduran and Kutija (2003) to analyze and formulate wave drag force absorbed by flexible trees. The cantilever beam theory was used to compute deflection of the flexible trees in their study. Thuy et al. (2009) denoted that the flow velocity and tsunami force are significantly reduced by a coastal forest of *Pandanus odoratissimus.* Husrin et al. (2012) measured the wave force on a unit plane area of coastal tree models in a flume and used an uncertain additive property to estimate wave force on the extended green belt width.

The significance and idea of conducting this research is reinforced by considerable reduction of destructive effects of tsunamis by coastal green belts as cited in the above reports. However, more experimental and numerical studies are required to provide design criteria for development of coastal green belt and mitigation of future tsunami effects.

In general, there are two approaches in hydrodynamics, the momentum and energy approaches. The momentum approach (sometimes called direct method) is typically suitable for fast unsteady flow cases such as drag force estimation of solitary coastal waves. Previous experimental studies of coastal protection by natural barriers are normally based on the energy approach (indirect method) and measurement of wave water level variation for estimation of wave attenuation and wave energy transfer to the coastal areas (i.e., in Huang et al., 2011). Using energy approach, extensive experiments are also conducted to study effect of aquatic vegetation on wave attenuation in coastal wet lands. In this regard, Akgul et al. (2013) and Oguz et al. (2013) simulated wind generated waves through emergent reed and estimated the wave attenuation. The wave attenuation was represented by wave transmission coefficient (defined as ratio of wave height after and before emergent reed zone) in their studies. The estimated wave transmitted coefficients varied 0.35–0.75 depending on the simulated reed characteristics and density. Using relationship between vegetation resistance and wave transmission coefficient, Augustin et al. (2009) and Anderson and Smith (2014) estimated drag coefficient for simulated emergent and near-emergent coastal marsh under irregular waves. Due to large variation of wave and simulated vegetation conditions, the reported drag coefficients varied 0.1–2.3 in their studies.

There are considerable inherent uncertainties due to calibration and measurements in the energy method. The direct measurement of the wave force on coastal barrier model, based on the momentum approach with much reduced uncertainties and design of a new frictionless system of drag measurement, are novel in this study. Clarification of coast and barrier effects on wave drag force with independent and measurable variables of wave-coast-barrier in practice enable better estimation and understanding of drag coefficient for calibration of the numerical models. The term of solitary breaking waves is used in this study to denote waves that break over the coastal vegetation canopy. The purpose of this study is to simulate coastal green belt with measureable variables in practice, and estimation of drag force, drag coefficient, and wave height attenuation for the solitary breaking waves on the green belt.

2. Materials and methods

2.1. Variables and modeling

The governing parameters for the interaction of single sea wave and coastal green belt include wave, vegetation, and shoreline geometry parameters, which are listed in Table 1 along with the appropriate measuring range of the experiment. A total number of 480 experiments were conducted in four different coast slopes with three different vegetation densities and one control condition (no vegetation) in this study.

Tree structure includes a rigid part known as the trunk, and a flexible part known as the crown (branches and foliage). The rigid and flexible parts cause considerable resistance to water flow and wave

Table 1
Modeling parameters for the present study.

Model parameter	Value
S Coast slope (%)	0, 3, 6, 9
D Vegetation density (%)	0, 30, 50, 100
H Wave height (m, above still water)	0.06–0.15
u Wave propagation velocity (m/s)	1.3–1.85
F Absorbed wave force (N)	10–153