WAVE SETUP ON VEGETATED BEACH: LABORATORY EXPERIMENTS

Yavuz Ozeren,[1] Daniel G. Wren[2] and Weiming Wu[3]

In this study, wave height evolution and wave setup were measured in a laboratory wave tank with a sloping beach covered with rigid and flexible artificial vegetation under regular and irregular wave conditions. The experiments were conducted in a 20.6 m long, 0.69 m wide and 1.22 m deep wave tank at the USDA-ARS National Sedimentation Laboratory, Oxford, MS, USA. Regular and irregular waves were generated using a computer controlled piston type wave generator. A plane wooden beach with a 1:21 slope was constructed at the down-wave end of the wave tank, 11.5 m away from the wave paddle. Rigid vegetation was constructed out of wooden dowels and flexible vegetation was constructed using polyurethane tubes. Both vegetation models were 3.1 mm in diameter and 0.2 m long and had a population density of 3,182 stems/m^2. The results were compared with those from experiments on a non-vegetated plane beach. Both rigid and flexible vegetation models reduced the wave height and wave setup substantially, but rigid vegetation typically performed better in reducing wave setup. For some of the experiments, no wave breaking was observed over the vegetated models, indicating that wave attenuation due to vegetation reduced the shoaling rate. For other experiments, wave breaking was observed and wave height attenuation was very small; however, wave setup was still significantly lower than in the plane beach experiments.

Keywords: wave setup, vegetated beach, laboratory experiments, wave height evolution

INTRODUCTION

Wave setup can contribute to elevated water levels during an extreme event. The magnitude of mean water rise above the still water level can be in the order of meters while the shoreward shift can be tens of meters (Harris, 1963; Komar, 1998). It was shown in a series of theoretical studies (e.g. Longuet-Higgins and Stewart, 1962, 1964) that wave setup is the response of mean water level to changes in the horizontal component of radiation stress during shoaling and wave breaking. Bowen et al. (1968) carried out small scale laboratory experiments in a wave tank and measured mean water level profile during wave breaking on a plane sloping beach. The results of these experiments were in close agreement with theory. Longut-Higgins (2004) theoretically investigated wave setup, including turbulent dissipation near the ripped seabed. Several studies have considered wave transformation through vegetation (e.g., Dalrymple et al, 1984; Asano et al., 1993; Ozeren et al., 2014); however, only a few studies accounted for the effect of vegetation on wave transformation in the surf zone (Mendez and Losada, 2004; Dean and Bender, 2006; Wu et al., 2011; van Rooijen et al., 2016). Dean and Bender (2006) theoretically showed that vegetation can reduce wave setup, and for some cases it may lead to wave setdown. The effect of vegetation on wave setup was addressed in previous studies, but they have not yet been experimentally validated. In this study, wave height evolution and wave setup were measured in a laboratory wave tank with a sloping beach covered with rigid and flexible artificial vegetation under regular and irregular wave conditions.

THEORETICAL BANKGROUND

Vegetation drag force

Consider a vegetated sloping beach covered with emergent vegetation, composed of a regular array of vertical circular cylinders of population density N_v (Figure 1). If the cylinder has a diameter D_v, the horizontal time varying vegetation drag force per unit volume acting on an incremental vertical length dz of the cylinder can be written as:

$$dF_D = \frac{1}{2} C_D \rho D_v u|u| dz \qquad (1)$$

where, C_D is the drag coefficient, u is the horizontal velocity, and ρ is the density of water. Time averaged drag force acting on the water column by a singe vertical cylinder can be found by integrating Equation 1 over the length of the cylinder and time averaging over a wave length.

$$F_v = \frac{1}{T} \int_t^{t+T} \int_{-h}^{\eta} \frac{1}{2} C_D \rho D_v u|u| dz dt \qquad (2)$$

---

[1] National Center for Computational Hydroscience and Engineering, University of Mississippi, 344 Brevard Hall, University, MS, 38677, USA

[2] United States Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, 598 McElroy Drive, Oxford, MS, 38655, USA

[3] Civil and Environmental Engineering, Clarkson University, Potsdam, NY, 13699, USA

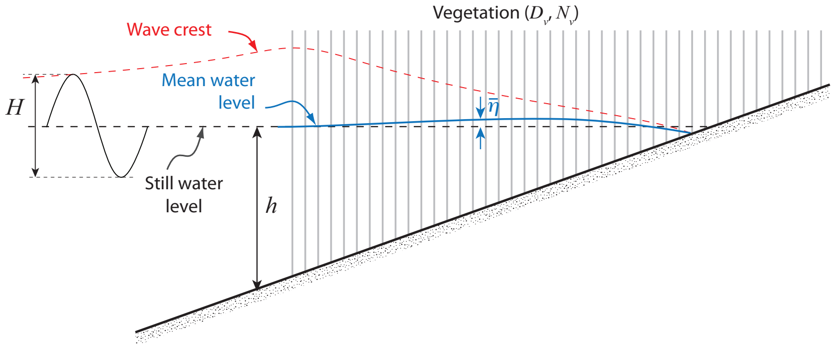

Figure 1. Definition of parameters for a vegetated plane beach.

The velocity, u, is defined by linear wave theory as:

$$u = \frac{H}{2}\sigma\frac{\cosh k(h+z)}{\sinh kh}\cos\sigma t \tag{3}$$

where H is wave height, g is gravitational acceleration, h is the still water depth, σ is wave angular frequency, and k is the wave number. Note that the integration of the Equation 2 up to the mean water level is zero, due to symmetry of the horizontal water particle velocities in a wave cycle. Following Dean and Bender (2006), the second integration can be solved by assuming the horizontal velocity near the free surface is:

$$u = \frac{H}{2}\sigma\frac{\cosh k(h)}{\sinh kh}\cos\sigma t \tag{4}$$

Substituting Equation 4 into Equation 2 and integrating, F_v is:

$$F_v = \frac{C_D\rho g D_v}{12\pi}\frac{H^3}{h}\frac{k}{\tanh k\,h} \tag{5}$$

The total drag force in shallow water ($kh \ll 1$) is:

$$f_v = F_v N_v = \frac{C_D\rho g a}{12\pi}\frac{H^3}{h} \tag{6}$$

where $a = D_v N_v$ = total frontal plant area per unit volume projected on a plane normal to u (Ozeren et al. 2014). Since C_D is assumed to be constant during the integration, it is a bulk drag coefficient, which is an empirical parameter that represents the total mean force created by all plants.

Momentum Equation

Radiation stress is the additional momentum flux due to wave related unsteady flow. If there is no energy loss by wave breaking or friction, the horizontal momentum flux on a horizontal bed is constant. When the waves approach a sloping beach, the gradient of the radiation stress is no longer zero, which leads to changes in the mean water level. On a vegetated beach, the horizontal momentum balance equation in a quasi-steady state can be written as:

$$\frac{S_{xx}}{dx} + \rho g(h+\bar{\eta})\frac{d\bar{\eta}}{dx} + f_v = 0 \tag{7}$$

where S_{xx} is the shoreward (positive -x) component of the radiation stress, $\bar{\eta}$ is the mean elevation of the free surface, and f_v represents the resisting force acting on the water column due to vegetation. Radiation stress can be written in terms of the horizontal energy flux as (Longuet-Higgins and Stewart,1962):

$$S_{xx} = \mathcal{F}\left(\frac{2}{c} - \frac{1}{2c_g}\right) \tag{8}$$

where c_g is the group velocity, and $c = \sigma/k$ is wave celerity. Horizontal energy flux can be written as:

$$\mathcal{F} = Ec_g \tag{9}$$

and wave energy density is:

$$E = \frac{1}{8}\rho g H^2 \tag{10}$$

Energy flux equation

Waves traveling through vegetation lose energy by doing work on the vegetation. In a quasi-steady state, assuming vegetation resistance is the only source of energy dissipation and the slope is mild enough that reflection is negligible, the energy balance equation is:

$$\frac{\partial \mathcal{F}}{\partial x} = -\varepsilon_v \tag{11}$$

where ε_v is the average energy dissipation per unit horizontal area. Equation 11 indicates that the average rate of energy dissipation through vegetation is equal to the gradient of the average energy flux. If the vegetation is approximated by vertically oriented rigid cylinders,

$$\varepsilon_v = \frac{1}{T}\int_t^{t+T}\int_{-h}^{\eta} F_D u\,dz\,dt \tag{12}$$

Integration of Equation 12 yields:

$$\varepsilon_v = C_D \rho a H^3 \frac{g\sigma}{36\pi}\left(\frac{5 + \cosh 2kh}{\sinh 2kh}\right) \tag{13}$$

In shallow water, Equation 13 can be reduced to:

$$\varepsilon_v = \frac{C_D \rho g^{3/2} a}{12\pi}\left(\frac{H^3}{h^{1/2}}\right) \tag{14}$$

Substituting Equations 8, 9 and 10 in Equation 7 and assuming $\bar{\eta} \ll h$,

$$-\rho g h \frac{d\bar{\eta}}{dx} = \frac{d}{dx}\left[\mathcal{F}\left(\frac{2}{c} - \frac{1}{2c_g}\right)\right] + f_v \tag{15}$$

since in shallow water, $c = c_g$ and c is constant. Substituting Equation 11,

$$\rho g h \frac{d\bar{\eta}}{dx} = \frac{3}{2}\frac{\varepsilon_v}{c} - f_v \tag{16}$$

Inserting Equations 6 and 14 into Equation 16, the gradient of the mean water level in shallow water can be found as:

$$\frac{d\bar{\eta}}{dx} = \frac{C_D a}{24\pi}\frac{H^3}{h^2} \tag{17}$$

Note that left hand side of Equation 17 is greater than zero. Since the mean water level in deep water is zero, positive gradient of the mean water level indicates wave setup which was also shown previously in Dean and Bender (2006). It is well known that on a plane sloping beach, as h decreases in the shoreward direction, the mean water level is lowered by the presence of waves if there is no energy dissipation (Longuet-Higgins and Stewart, 1962). This small reduction in the mean water level, often referred as “set down”, is due to the increasing radiation stress during shoaling. Equation 16 shows that energy dissipation due to vegetation drag increases mean water level gradient while the resisting force due to vegetation decreases, and the overall effect is wave setup. The preceding derivation is based on linear waves and is not valid when nonlinearities are significant. It was shown in Dean and Bender (2006) that forces on the water column by vegetation drag are larger for nonlinear waves, relative to those of the linear waves. It was also noted that nonlinearities increase with decreasing h. If the relative contribution of f_v in Equation 16 increases in the shoreward direction then gradient of the mean water level is expected to decrease. This is validated with the experimental results presented in the next section.

EXPERIMENTAL SETUP

The experiments were conducted in a 20.6 m long, 0.69 m wide and 1.22 m deep wave tank at the USDA-ARS National Sedimentation Laboratory, Oxford, MS, USA (Figure 2). Waves were generated using a computer controlled piston type wave generator. A plane wooden beach with a 1:21 slope was constructed at the down-wave end of the wave tank, 11.5 m away from the wave paddle.

Two different types of materials were used for the vegetated beach experiments. Rigid vegetation was constructed out of wooden dowels and flexible vegetation was constructed using polyurethane tubes (Figure 3). Both of the vegetation models were 3.1 mm in diameter and 0.2 m long and had a population density of 3,182 stems/m^2. Water level was measured at 30 Hz using an array of movable wave staffs with 0.3 mm resolution.

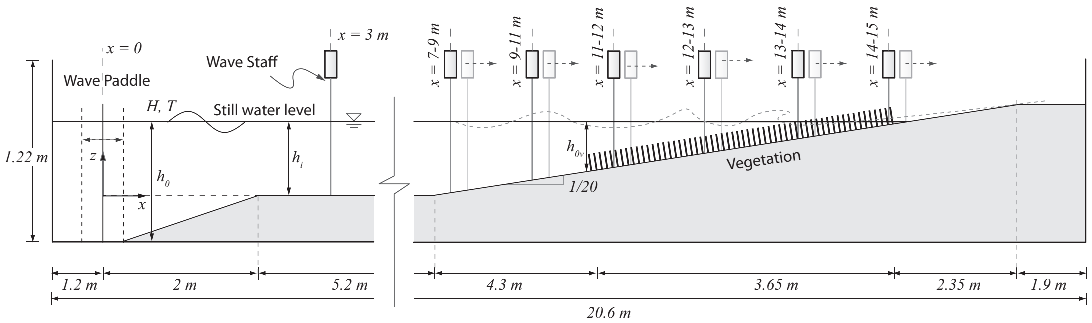

Figure 2. Description of the experimental setup.

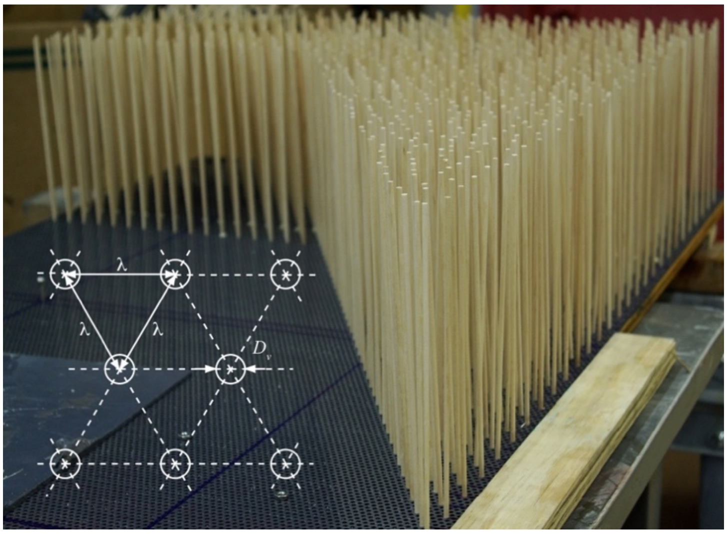

Figure 3. Rigid vegetation and a diagram showing their arrangement.

RESULTS AND DISCUSSIONS

Experiments were carried out for 24 regular and 7 irregular wave conditions of varying wave heights and periods at 0.4 m water depth. The ranges of wave heights and periods for the regular wave experiments were H = 0.02 m - 0.15 m and T = 1.2 s - 3 s. For the irregular experiments, H_{m0} = 0.04 m - 0.08 m and T_p = 1.2 s - 2.4 s. Each regular wave experiment was repeated three times to reduce uncertainty. The irregular waves were generated based on the JONSWAP spectrum. The same set of wave conditions was generated for the non-vegetated beach and the vegetated beach with rigid and flexible artificial vegetation. Five $100T_p$ long, where T_p is the peak wave period, irregular time series signals were used to generate approximately 500 waves for each condition. In order to calculate irregular wave properties, five wave spectra corresponding to the recorded wave height time series at each gauge were averaged in the frequency domain. The same input time series signals were repeated for non-vegetated and vegetated beach runs. A band-pass Butterworth filter was used to remove very high (~1/*T*>3) and very low (~1/*T*< 0.1) frequencies from the wave height records.

Individual wave heights were defined as the difference between the highest and lowest water surface elevations between two zero down-crossings in the recorded water surface time history. For irregular waves, the energy based significant wave height was defined by:

$$H_{m0} = 4\sqrt{H_{m0}m_0} \qquad (18)$$

where m_0 is the zero-th moment of the spectrum. Mean water level was defined as the average water surface elevation between each pair of zero down-crossings.

Results of both rigid and flexible vegetation experiments were compared with those from experiments on a non-vegetated plane beach (control experiments). In what follows, the results of two regular wave and two irregular wave experiments for each beach profile configuration are presented for comparison. Figure 4 shows pictures of the beach profile without vegetation and with rigid and flexible vegetation for a typical experiment. The incident wave height, wave period and the phases were the same in all three cases. The breaker in Figure 4a is not present in Figure 4b and has been partially dissipated in Figure 4c. On the non-vegetated plane beach, typical wave shoaling was followed by either spilling or plunging type breakers. On the vegetated beaches, shoaling and wave breaking were partially or completely eliminated. When partial wave breaking was observed on the vegetated beaches, the breaking point shifted shoreward relative to the control experiments with the same incident wave properties. Run-up distance was also considerably shorter on the vegetated beaches when compared to that of the control experiments.

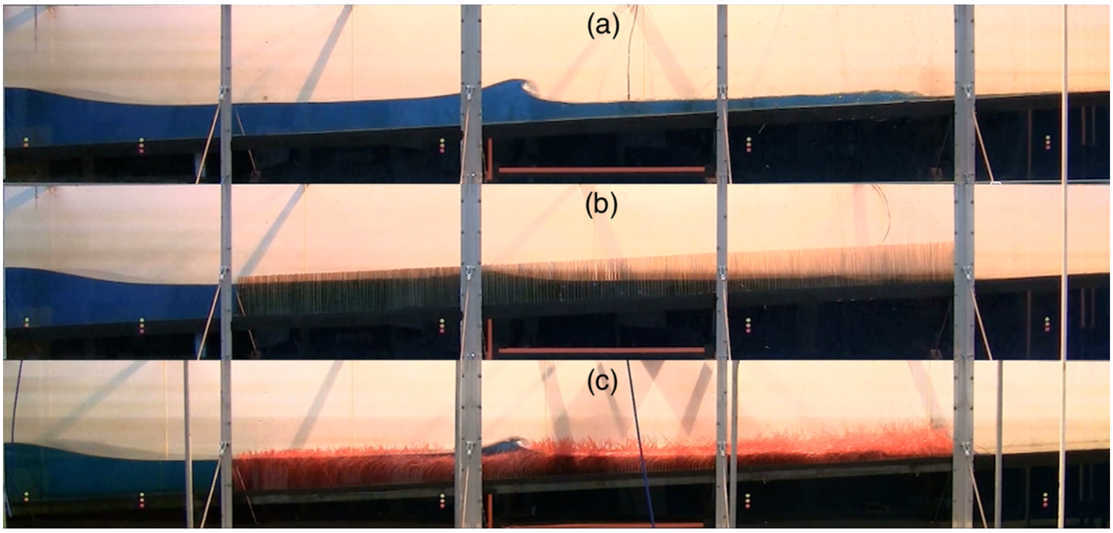

Figure 4. A typical experiment on (a) plane beach, (b) covered with rigid vegetation, and (c) flexible vegetation.

In Figure 5, dimensionless wave height (top plots) and mean water level (bottom plots) for rigid and flexible vegetation experiments with regular waves are compared with control experiments. For all three beach types, the incident wave heights were 0.053 m in Figure 5a and 0.083 m in Figure 5b. Wave periods were 1.8 s for all of the experiments shown in Figure 5. Each marker on the wave height plots designates a wave height measurement station. The markers are not shown in the mean water level plots for simplicity. The vertical dotted lines indicate the boundaries of the vegetation field, and the beach face is shown with a solid line in the mean water level plots. Seaward of the vegetation field, the wave height profiles of the control and vegetated beach experiments were similar in Figures 5a and 5b. The wave height declined in both rigid and flexible vegetation fields, but the attenuation rate was higher for rigid vegetation. The wave heights attenuated without breaking along the vegetation field and completely diminished at the shoreline. The mean water level was lowered seawards of the surf zone along the entire wave tank, and increased inside the surf zone towards the shoreline with a constant gradient, such that there was wave setup. A line was fitted to the rising section of the mean water, and extended to the beach face to reveal the maximum wave setup which is shown with dashed lines in Figure 5. The ratio of the mean water level gradient to the beach slope in the surf zone is approximately -0.16 for both experiments, which is in good agreement with the previously reported value of -0.15 (Longuet-Higgins and Steward, 1963). The mean water level outside the surf zone declined, most likely to conserve the total volume inside the wave tank.

Shoreward of the rigid vegetation field, the mean water level increased (Figure 5). Inside the vegetation field, the mean water level first increased and then gradually declined from positive to negative values, such that there was "setdown". The setdown for the rigid vegetation experiments is slightly lower in Figure 5a than the setdown for the same experiments with larger wave height in Figure 5b. Because the nonlinear wave effects are expected to be more significant for higher wave heights with the same wave periods, slightly higher setdown in Figure 5b is considered to be agreement with Dean and Bender (2006). The mean water level seaward of the flexible vegetation field in Figure 5 is below the still water level, but higher than the mean water level of the control experiments. Inside the flexible vegetation field, the mean water level is higher than in the rigid vegetation field, but wave setup is significantly reduced relative to the control experiments. Wave setup for the flexible vegetation is relatively higher in Figure 5b than in Figure 5a.

Figures 6a and 6b show two examples of irregular wave experiments. The vertical axis values are scaled by the energy based significant wave height, H_{m0}. Dimensionless wave height profiles for experiments with irregular waves in Figure 6 were in general similar to that of the regular wave experiments, except that the profiles of the control experiments have relatively wider and lower peak in the shoaling region compared to wave height profiles of the regular waves. Irregular waves are composed of a range of wave heights each of which break at a different height; hence, the breaking point for each component is spread along the beach face which explains the difference in wave height evulsions. The wave heights decayed with a similar profile inside the rigid and flexible vegetation zones for the experiment in Figure 6, but the flexible vegetation had slightly lower wave height and showed modulations. No wave breaking was observed during the experiments shown in Figure 6. Shoaling wider and lower peak in the shoaling region compared to shoaling profiles of the regular waves. Figure 6 shows that, the mean water level was lowered seawards of the breaking zone with peak setdown in the shoaling region during the control experiments. Inside the surf zone, the mean water level increased significantly showing a clear wave setup. The mean water level had an increasing gradient in the shoreward direction in both Figures 6a and 6b. For the experiments with vegetation shown in Figure 6, little or no setdown was observed seaward of the vegetation zone. Setup was mostly eliminated inside the rigid vegetation, while it was significantly lowered inside the flexible vegetation.

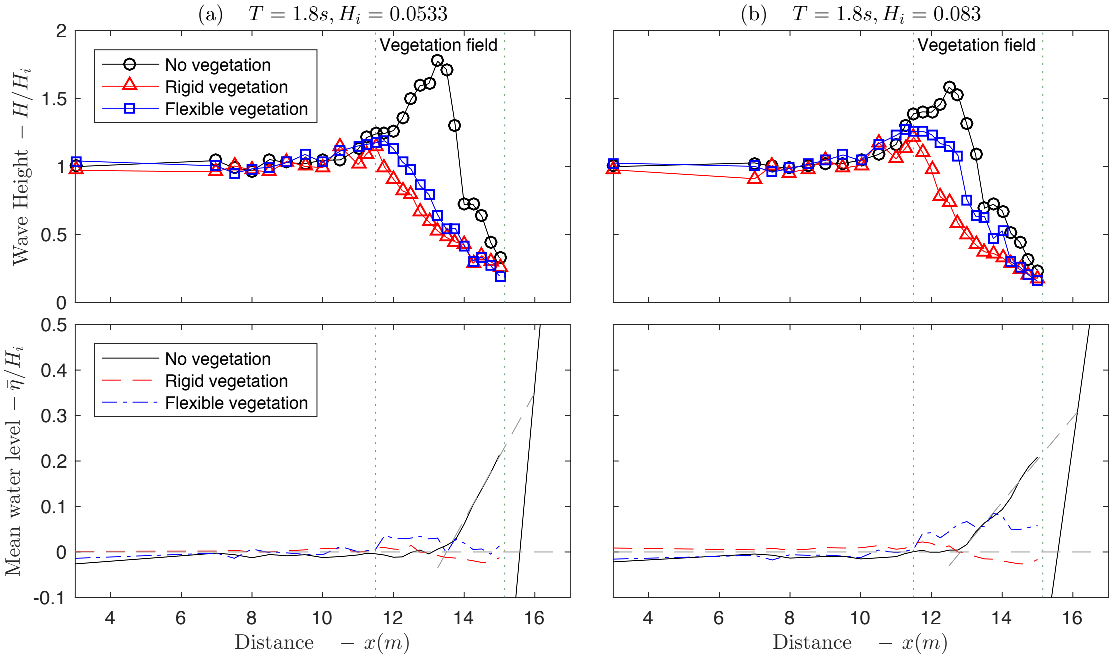

Figure 5. Wave height transformation and wave setup for two regular wave experiments.

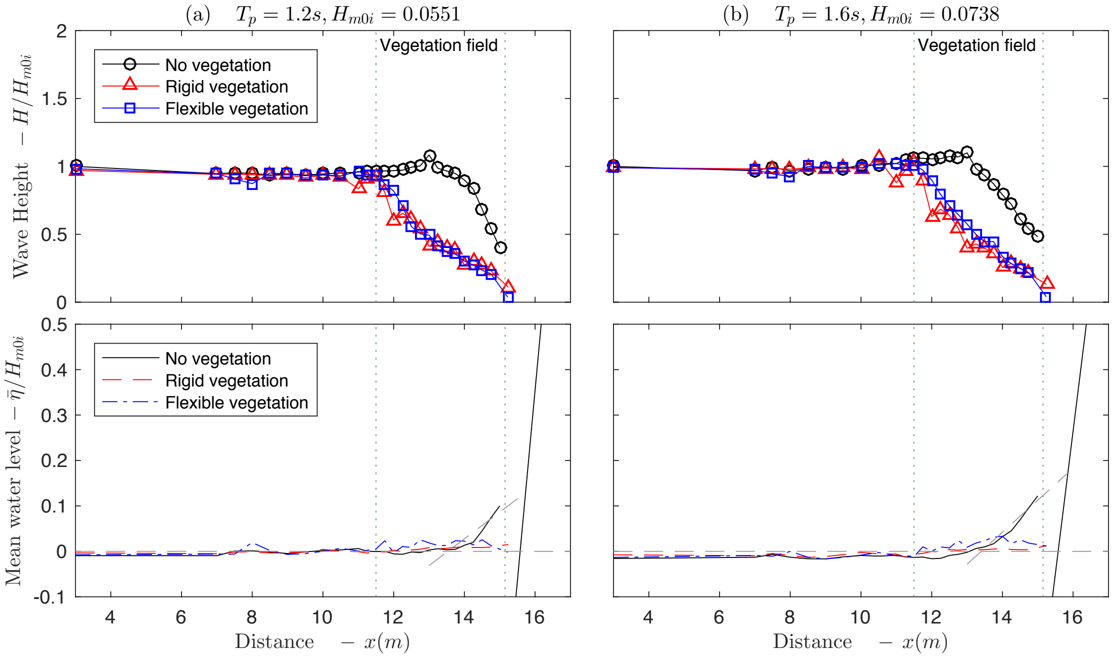

Figure 6. Wave height transformation and wave setup for two regular wave experiments.

The results of the plane beach experiments agree with existing theory on wave setup (e.g. Longuet-Higgins and Stewart, 1962), such that seaward of the surf zone, where the energy losses are small, the mean water level is depressed relative to the still water level. Inside the surf zone, mean water level increased with an approximately constant gradient. The results of the vegetated beach experiments can also be linked to the existing theory that was presented. Energy dissipation by vegetation can diminish shoaling effects and partially or fully eliminate wave breaking. The energy dissipation by vegetation and vegetation drag force also influence the mean water level. Since wave breaking is eliminated by gradually dissipating energy at a much smaller rate, wave setup along the shoreline is negligibly small. If vegetation is the only source of energy dissipation, Equation 17 is in theory valid up to the shoreline. This is limited by nonlinear waves that are more pronounced at shallower depths. The resulting horizontal drag force due to nonlinear waves can be much larger than that of the linear waves (Dean and Bender, 2006). In Equation 16, for the same energy dissipation, larger vegetation drag can lead to negative values of mean water gradient. The experimental results presented in Figure 5 validate these theoretical findings.

CONCLUSIONS

In this study, laboratory experiments were carried out in a laboratory wave tank to investigate wave height evolution and wave setup on a vegetated beach with constant slope. Rigid and flexible material were used to simulate vegetation elements. The experimental result from regular and irregular waves, along with summary of the related theory, were presented. The results showed that vegetation substantially reduced wave setup on a sloping beach, and, for some cases, led to setdown. The energy dissipation due to vegetation was sufficiently high to prevent wave breaking. The results were in good agreement with the theory that was presented. Wave energy was dissipated gradually across the beach without wave breaking, and the gradient of the momentum flux was balanced by vegetation drag force. It was shown in Dean and Bender (2006) that the relative magnitude of the resisting vegetation drag depends on the nonlinear wave effects, which may lead to setdown as observed in some of the experiments presented here.

ACKNOWLEDGMENTS

This research was supported by the US Department of Homeland Security–sponsored Southeast Region Research Initiative at the US Department of Energy's Oak Ridge National Laboratory, and in part by the USDA Agriculture Research Service under the Specific Research Agreement No. 58-6408-1-609 administered by the USDA-ARS National Sedimentation Laboratory and The University of Mississippi. Reza Marsooli, Allan Barger, Austin Patton, Glenn Gray, Will Simpson, are recognized for their efforts in preparation of the experiments.

REFERENCES

Asano, T., Tsutsui, S., and Sakai T. 1988. Wave damping characteristics due to seaweed. *Proceedings of the 25th International Coastal Engineering Conference* (ICEC' 88).

Bowen, A.J., Inman, D.L. and Simmons, V.P., 1968. Wave 'set-down'and set-Up. *Journal of Geophysical Research*, *73*(8), pp.2569-2577.

Dalrymple, R.A., Kirby, J.T. and Hwang, P.A., 1984. Wave diffraction due to areas of energy dissipation. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *110*(1), pp.67-79.

Dean, R.G., and Bender, C.J. 2006. Static wave setup with emphasis on damping effects by vegetation and bottom friction. *Journal of Coastal Engineering* 53, 149-156.

Harris, D.L., 1963. *Characteristics of the hurricane storm surge*. Department of Commerce, Weather Bureau.

Komar, P. D. 1998. *Beach Processes and Sedimentation*. Prentice-Hall. Inc., Englewood Cliffs, NJ.

Longuet-Higgins, M.S. and Stewart, R.W., 1962. Radiation stress and mass transport in gravity waves, with application to 'surf beats'. *Journal of Fluid Mechanics*, *13*(04), pp.481-504.

Longuet-Higgins, M.S. and Stewart, R.W., 1964, August. Radiation stresses in water waves; a physical discussion, with applications. In *Deep Sea Research and Oceanographic Abstracts* (Vol. 11, No. 4, pp. 529-562). Elsevier.

Longuet-Higgins, M.S., 2005. On wave set-up in shoaling water with a rough sea bed. *Journal of Fluid Mechanics*, *527*, pp.217-234.

Mendez, F. J. and Losada., I. J., 2004. An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. *Coastal Engineering*, 51: 103-118.

Ozeren, Y., Wren, D.G. and Wu, W., 2014. Experimental investigation of wave attenuation through model and live vegetation. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *140*(5), p.04014019.

van Rooijen, A.A., McCall, R.T., van Thiel de Vries, J.S.M., van Dongeren, A.R., Reniers, A.J.H.M. and Roelvink, J.A., 2016. Modeling the effect of wave-vegetation interaction on wave setup. *Journal of Geophysical Research: Oceans*, *121*(6), pp.4341-4359.

Wu, W., Ozeren, Y., Wren, D., Chen, Q., Zhang, G., Holland, M., Ding, Y., Kuiry, S.N., Zhang, M., Jadhav, R. and Chatagnier, J., 2011. Investigation of surge and wave reduction by vegetation. Phase I Report for SERRI Project No. 80037, The University of Mississippi, MS, 315p.