Available online at www.sciencedirect.com
SCIENCE DIRECT®
Coastal Engineering 53 (2006) 149 – 156
Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers
www.elsevier.com/locate/coastaleng

Static wave setup with emphasis on damping effects by vegetation and bottom friction

Robert G. Dean [a,*], Christopher J. Bender [b]

[a] *Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611-6590, USA*
[b] *Taylor Engineering, 9000 Cypress Green Drive, Jacksonville, FL 32256, USA*

Available online 22 November 2005

Abstract

Wave setup can contribute significantly to elevated water levels during severe storms. In Florida we have found that wave setup can be 30% to 60% of the total 100-year storm surge. In areas with relatively narrow continental shelves, such as many locations along the Pacific Coast of the United States, wave setup can be an even larger proportionate contributor of anomalous water levels during major storms. Wave setup can be considered as comprising two components, with the first being the well-known static wave setup resulting from the transfer of breaking wave momentum to the water column. The second, oscillating component, is a result of nonlinear transfer of energy and momentum from the primary (linear) spectrum to waves with length and time scales on the order of the wave groups.

Static wave setup is the focus of this paper with emphasis on effects due to internal or surface forces that act on the wave system and cause both dissipation of wave energy and transfer of momentum. In particular, the effects of wave damping by vegetation and bottom friction are considered. Linear wave theory is applied to illustrate these effects and, for shallow water waves, the setup is reduced by two-thirds the amount that would occur if the same amount of energy dissipation occurred in the absence of forces. Effects of nonlinear waves are then considered and it is found, for a shallow water wave of approximately one-half breaking height, that a wave setdown rather than setup occurs due to damping by vegetation and bottom friction.

The problem of wave setup as waves propagate through vegetation was stimulated by studies to establish hazard zones associated with 100-year storm events along the shorelines of the United States. These storms can generate elevated water levels exceeding 4 to 6 m and can result in overland wave propagation. As these waves propagate through vegetation and damp, the question arose as to the contribution of this process to elevated mean water levels through additional wave setup.

Keywords: Wave setup/setdown; Momentum fluxes; Vegetation damping; Bottom friction; Nonlinear waves

1. Introduction

Wave setup has been investigated theoretically, through laboratory experiments, and by field measurements and observations. The original theoretical contributions were due to Longuet-Higgins and Stewart (1960, 1962, 1963, 1964) in their introduction of the radiation stresses which represent the excess momentum fluxes due to waves.

There have been numerous laboratory investigations of static and dynamic setup. Only a few of those of particular relevance to this paper are referenced here. Bowen et al. (1968) conducted some of the first laboratory tests with periodic waves and reported reasonably good agreement with linear theory predictions although the ratio of maximum setup to breaking wave height ranged from 0.27 to 0.42, larger than normally considered. Battjes (1972) investigated wave setup for irregular waves and found less setup than predicted by linear theory; these differences were considered to be possibly due to air bubbles in the manometers used to conduct the measurements. Stive and Wind (1982) carried out detailed measurements of setup, wave forms and velocities for periodic waves. The measurements allowed direct calculation of the radiation stresses. Measured setup was compared with linear and nonlinear theories and with the radiation stress gradients based on measurements. Best agreement was found between measurements and radiation stress gradients based on measurements, followed by nonlinear theories. James (1974) has applied a combination of Third Order Stokes and Cnoidal

* Corresponding author.
E-mail address: dean@coastal.ufl.edu (R.G. Dean).

0378-3839/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.coastaleng.2005.10.005

wave theories to examine the effects of wave nonlinearities on wave setup. Through theoretical and laboratory investigations, Svendsen and colleagues (Svendsen and Hansen, 1976; Svendsen et al., 1978; Hansen and Svendsen, 1979; Svendsen, 1984) have contributed broadly to wave setup including issues of wave breaking, nonlinearities, and the roller model all of which have improved significantly our quantitative understanding of wave setup mechanisms.

The earliest field studies of dynamic wave setup/setdown were reported by Munk (1949) and Tucker (1950). More recent field investigations of static and dynamic setup include those of Goda (1975), Hansen (1978), Guza and Thornton (1981), Holman and Sallenger (1985), Davis and Nielsen (1988), Nielsen (1989), Lentz and Raubenheimer (1999), Dunn and Nielsen (2000), Raubenheimer et al. (2001), Ruggiero et al. (2001) and Stockdon et al. (2004) among others. A summary of available setup/setdown literature at the time was provided by Holman (1990).

2. Theoretical relationships

The governing equation for wave setup, $\bar{\eta}$, including the effects of extraneous forces can be written as

$$\rho g(h+\bar{\eta})\frac{\partial \bar{\eta}}{\partial x} = -\frac{\partial S_{xx}}{\partial x} + f_x \tag{1}$$

in which, S_{xx} is the flux in the x direction of the x component of wave related momentum, f_x represents any extraneous force per unit plan area acting on the water column, ρ is the mass density of water and h is the still water depth, see Fig. 1. The extraneous force could be internal such as due to waves propagating through vegetation (here considered as cylinders) or external such as bottom friction. These forces depend on the wave kinematics and thus the wave theory being applied. For purposes here, the effects of both linear and nonlinear theories will be examined. The sign of the extraneous force is taken as positive if acting on the water column in the direction of wave propagation and its effect in contributing to a positive setup can be considered as similar to a wind stress that acts landward.

The general form for the gradient of S_{xx} is (Longuet-Higgins, 1973; Battjes, 1974)

$$-\frac{\partial S_{xx}}{\partial x} = \frac{\varepsilon}{C} - h\frac{\partial}{\partial x}\left(\frac{kE}{\sinh 2kh}\right) \tag{2}$$

in which ε is the wave energy dissipation rate per unit surface area, C is the wave celerity, k is the wave number ($=2\pi/L$), L is the wave length, E is the wave energy density, h is the still water depth and $\bar{\eta}$ is the wave setup. For the case of uniform depth considered here,

$$-\frac{\partial S_{xx}}{\partial x} = \frac{\varepsilon}{C_G}\left(2n - \frac{1}{2}\right) \tag{3}$$

where n is the ratio of group velocity, C_G, to wave celerity, C.

The equation for wave energy conservation is

$$\frac{\partial E}{\partial t} + \frac{\partial (EC_G)}{\partial x} + \varepsilon = 0 \tag{4}$$

and since we consider steady state, $\partial E/\partial t = 0$.

3. General considerations of surf zone profile slope

Inspection of Eq. (1) illustrates that the greater the water depth in which the momentum is transferred, the less the wave setup. This places a greater emphasis on breaking wave models. The most simple breaking wave model is the saturation model in which the breaking wave height is proportional to the local total water depth. However, it is well known that waves will break on steep slopes with greater wave heights and on milder slopes with smaller wave heights than predicted by the saturation model. For example, Nelson (1993) has shown that, based on field and laboratory measurements on horizontal beds, the ratio of the largest stable wave to uniform water depth is approximately 0.55, considerably smaller than on steep slopes. Thus the wave setup is expected to be less on milder slopes. An example is provided by Hurricane Ivan in September 2004 in which a maximum deep water significant

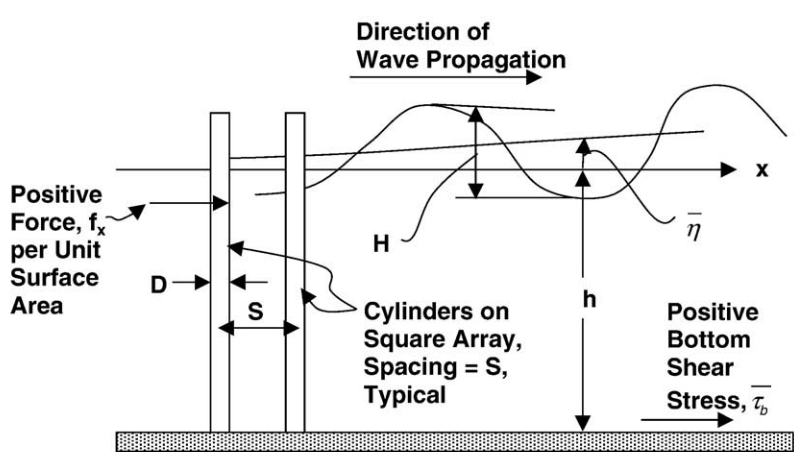

Fig. 1. Definition sketch of wave interaction with cylindrical elements and shear stress on bottom. Directions of force, f_x, and shear stress, $\overline{\tau_b}$, are shown positive as they act on the water column.

wave height in excess of 16 m was measured by a deep water buoy; however, based on high water marks, the wave setup due to this storm is believed to be much less than predicted by the saturation breaking model (total documented storm surge including wave setup and wind surge $\approx$4 m).

4. Effects of energy dissipation by vegetation and bottom friction

4.1. Linear wave theory

4.1.1. Vegetation elements

Consider the propagation of waves through vegetation elements idealized by an array of cylinders on a square array with spacing, S, see Fig. 1.

4.1.1.1. Energy losses. The local average wave energy loss per unit area, $-C_G\partial E/\partial x$ ($=\varepsilon$), is given by

$$-C_G\partial E/\partial x = \varepsilon = \frac{1}{TS^2}\int_t^{t+T}\int_{-h}^{\eta} F_D u dz dt = \frac{C_D\rho D}{2TS^2}\int_t^{t+T}\int_{-h}^{\eta}|u|u^2 dz dt \approx \frac{C_D\rho D}{2TS^2}\int_t^{t+T}\int_{-h}^{0}|u|u^2 dz dt \quad (5)$$

with the latter equation correct to third order in wave height. In Eq. (5), η is the instantaneous water surface displacement about the mean water level, u is the horizontal water particle velocity, F_D is the drag force, C_D is the drag coefficient (O(1)) and T is wave period. Other terms are defined in Fig. 1. Applying linear wave theory equations for horizontal water particle velocity and integrating,

$$\varepsilon = \frac{C_D\rho g D H^3\sigma}{36\pi S^2 \sinh 2kh}(5+\cosh 2kh) \quad (6)$$

where σ is the wave angular frequency (σ=2π/T). Since S_{xx}=E(2n − 1/2)

$$-\frac{\partial S_{xx}}{\partial x} = \frac{\varepsilon}{C_G}(2n-1/2) = \frac{C_D\rho g D H^3\sigma}{36\pi S^2 C_G \sinh 2kh}(2n-1/2)(5+\cosh 2kh). \quad (7)$$

4.1.1.2. Forces on vegetative elements. Applying linear wave theory to this system, the time averaged drag force for one vegetation element (cylinder), F_x, is given by:

$$F_x = -\frac{C_D\rho D}{2T}\int_t^{t+T}\int_{-h}^{\eta} u|u| dz dt = -\frac{C_D\rho D}{2T}\left[\int_t^{t+T}\int_{-h}^{0} u|u| dz dt + \int_t^{t+T}\int_{0}^{\eta} u|u| dz dt\right] \quad (8)$$

The first term on the lower line is zero as a result of the symmetry of the horizontal water particle velocities of linear water wave theory, which leaves

$$F_x \approx -\frac{C_D\rho D}{2T}\int_t^{t+T} u|u|\eta dt \quad (9)$$

where the integrand has been assumed uniform over the (small) vertical distance, η. Further approximating the horizontal velocity in the vicinity of the free surface by

$$u(0,t) = \frac{H}{2}\sigma\frac{\cosh kh}{\sinh kh}\cos\sigma t \quad (10)$$

and integrating,

$$F_x = -\frac{C_D\rho g D H^3 k}{12\pi \tanh kh}. \quad (11)$$

The average force per unit surface area, f_x, in water of arbitrary depth is

$$f_x = \frac{F_x}{S^2} = -\frac{C_D\rho g D H^3 k}{12\pi S^2 \tanh kh} \quad (12)$$

4.1.1.3. Wave setup due to interaction with vegetation elements. Inserting Eqs. (7) and (12) into Eq. (1) yields for the wave setup due to vegetation

$$\frac{\partial\bar\eta}{\partial x} = \frac{1}{\rho g(h+\bar\eta)}\frac{C_D\rho g D H^3 k}{12\pi S^2 \tanh kh}\times\left(\frac{(2n-1/2)}{3n}\frac{(5+\cosh 2kh)}{(1+\cosh 2kh)}-1\right) \quad (13)$$

which, in shallow water, is given by

$$\frac{\partial\bar\eta}{\partial x} = \frac{1}{\rho g(h+\bar\eta)}\frac{C_D\rho g D H^3}{12\pi S^2 h}\left(\frac{3}{2}-1\right) \quad (14)$$

with the first term in the brackets representing the setup due to wave energy dissipation and the second a setdown due to the force exerted by the cylinder on the water column. Thus, the effect of the vegetation force in shallow water is to reduce the setup to one-third of the amount that would have occurred due to the same amount of energy dissipation in the absence of a force. The deep water asymptote is a *setdown* with the quantities in the large parentheses in Eq. (13) approaching −2/3. The setup changes from positive to negative at kh=0.788.

4.1.2. Wave setup caused by bottom shear stress

4.1.2.1. Average bottom shear stress. For the case of linear waves propagating over a horizontal bottom with a viscous boundary layer, Phillips (1966) has shown that a streaming near bottom velocity exists which causes a net bottom shear force, $\overline{\tau_b}$, on the water column counter to the wave propagation direction, given by

$$\overline{\tau_b} = -\frac{\rho \nu \beta \sigma H^2 k}{8\sinh^2 kh} \tag{15}$$

in which $\beta \equiv \sqrt{\frac{\sigma}{2\nu}}$ and ν is the kinematic molecular viscosity or an eddy viscosity.

4.1.2.2. Energy losses. The rate of energy dissipation per unit surface area within the boundary layer, ε, is given by the time average of the product of the bottom shear stress and the near bottom horizontal velocity, which reduces to

$$\varepsilon = -C_G \frac{\partial E}{\partial x} = \frac{\rho \nu \beta}{2}\left(\frac{Hgk}{2\sigma \cosh kh}\right)^2. \tag{16}$$

4.1.2.3. Wave setup due to bottom shear stress. Following the same procedures as for wave energy dissipation by vegetation elements, the wave setup is

$$\begin{aligned}\frac{\partial \bar{\eta}}{\partial x} &= \frac{1}{\rho g(h+\bar{\eta})}\left(\frac{\varepsilon}{C_G}(2n-1/2)+\overline{\tau_b}\right)\\ &= \frac{1}{\rho g(h+\bar{\eta})}\frac{\rho g \nu \beta H^2 k}{4C\sinh 2kh}\left(\frac{(2n-1/2)}{n}-1\right).\end{aligned} \tag{17}$$

In shallow water, this equation reduces to

$$\frac{\partial \bar{\eta}}{\partial x} = \frac{1}{\rho g(h+\bar{\eta})}\frac{\rho \nu \beta H^2 C}{8h^2}\left(\frac{3}{2}-1\right). \tag{18}$$

The first and second terms in the parentheses represent the contributions to the wave setup of the energy dissipation and bottom friction due to bottom streaming, respectively. Thus, in shallow water, similar to the case of vegetation effects, the wave setup due to bottom friction is one-third of the amount that would occur for the same energy dissipation in the absence of a force. The deep water asymptote of the expression in the large parentheses in the second of Eq. (17) is zero.

4.2. Nonlinear waves and their effects

4.2.1. Wave energy

An interesting characteristic of waves is that a nonlinear wave has less energy density than a linear wave of the same height (James, 1974; Dean, 1974). This can be seen easily through examination of the potential wave energy density, PE, given, for both linear and nonlinear waves of period, T, as

$$\mathrm{PE} = \frac{\rho g}{T}\int_t^{t+T}\frac{\eta^2}{2}dt. \tag{19}$$

Nonlinear waves are known to be characterized by more peaked crests and flatter and broader troughs. This characteristic becomes more accentuated with greater nonlinearity, i.e. higher waves and shallower water conditions. In the limit, as a wave form approaches a delta function, PE approaches zero! Although this argument has been made here for the potential energy component of the total wave energy it also applies to the kinetic energy density, KE, because for conservative systems, the total energy is equally partitioned between the potential and kinetic energy components.

Results will be presented based on the forty cases included in the Stream Function tables (Dean, 1965, 1974; Dalrymple, 1974) although other nonlinear wave theories would serve equally well. The stream function tables include forty combinations of wave conditions in non-dimensional form and tabulate many results of engineering and scientific interests. The conditions encompass ten values of relative

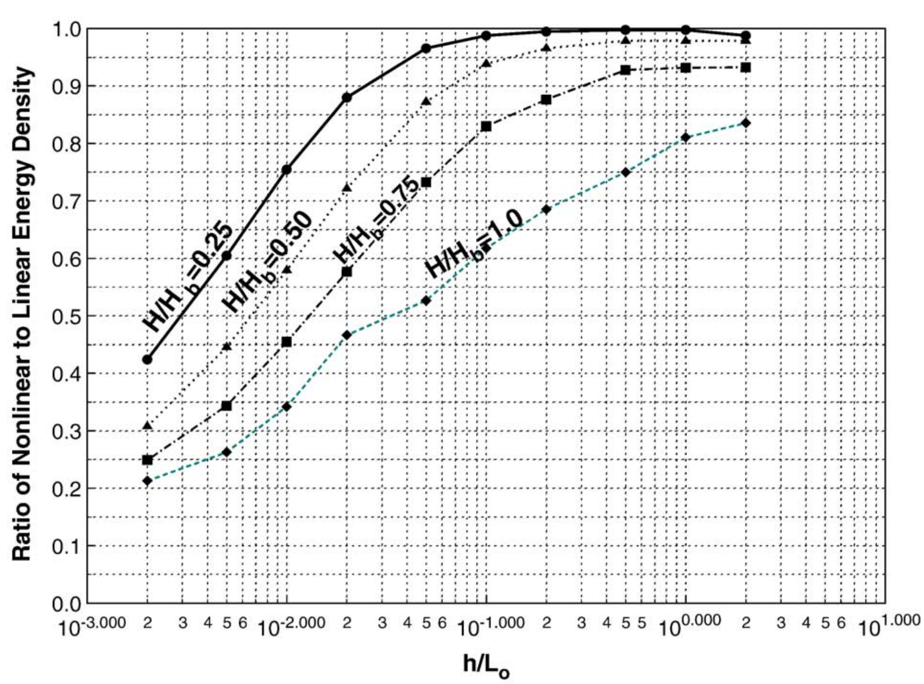

Fig. 2. Ratio of nonlinear to linear wave energy density for forty stream function wave combinations.

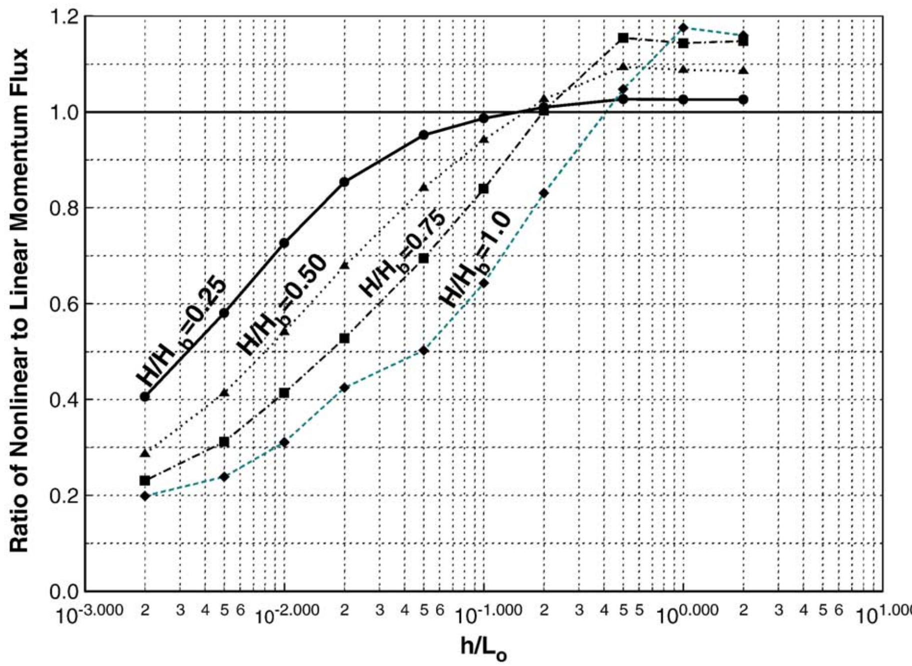

Fig. 3. Ratio of nonlinear to linear wave momentum flux, S_{xx}, for forty stream function wave combinations.

water depth in the form h/L_o and, for each of these h/L_o values, four wave heights: one-quarter, one-half, three-quarters and full breaking height (L_o = deep water linear wave length). Fig. 2 presents the ratio of total nonlinear wave energy to linear wave energy. It is seen that this ratio is always less than unity with the deviation being greater for shallow water and near breaking conditions. In Fig. 2, H_b is the breaking wave height with the shallow water and deep water limits given, respectively, by $H_b = \kappa h$ (here $\kappa = 0.78$) and $H_b = 1/7 L'_o$, where L'_o is the nonlinear deep water breaking wave length, $L'_o \approx 1.2 L_o$.

4.2.2. Nonlinear wave effects on S_{xx}

This effect of smaller wave energy densities for nonlinear waves is also characteristic of the momentum flux component, S_{xx}. This is not surprising as S_{xx} is also a second order quantity in wave height and depends on some of the same terms as the wave energy density. Fig. 3 presents the ratio of the nonlinear to linear S_{xx} terms where it is seen that the same general characteristics occur for this ratio as for the wave energy density. A difference is that for deeper water conditions, the nonlinear waves are characterized by a greater momentum flux

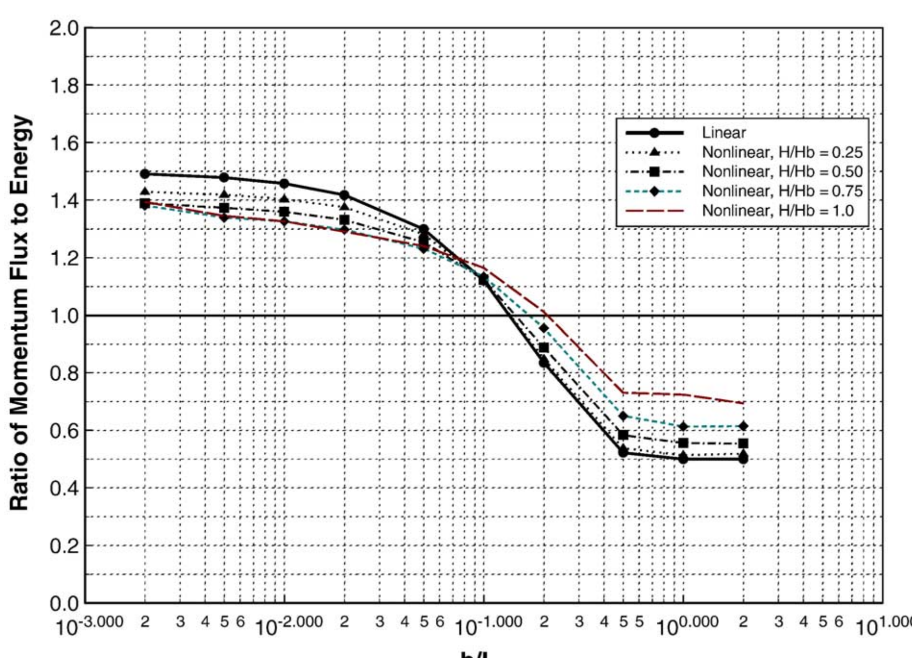

Fig. 4. Ratio of nonlinear momentum flux to nonlinear wave energy and the linear expression for this ratio.

than for linear waves. This is due primarily to the large water particle velocities in the wave crest region for nonlinear waves. In view of the results in Fig. 3, it is expected that in shallow to intermediate water conditions, the wave setup would be reduced substantially due to the momentum flux characteristics of nonlinear vs linear water waves.

To illustrate the similarity in reduction of energy density and momentum flux due to nonlinearities, Fig. 4 presents the ratios of nonlinear momentum flux to nonlinear wave energy density for the same forty wave cases. The linear ratio of S_{xx} to energy density, E, is also included in the figure where it is seen that the ratios of nonlinear quantities are in much better agreement with the linear relationship

$$\frac{S_{xx}}{E} = (2n - 1/2) \tag{20}$$

which illustrates the quantitatively similar nonlinear effects on S_{xx} and E.

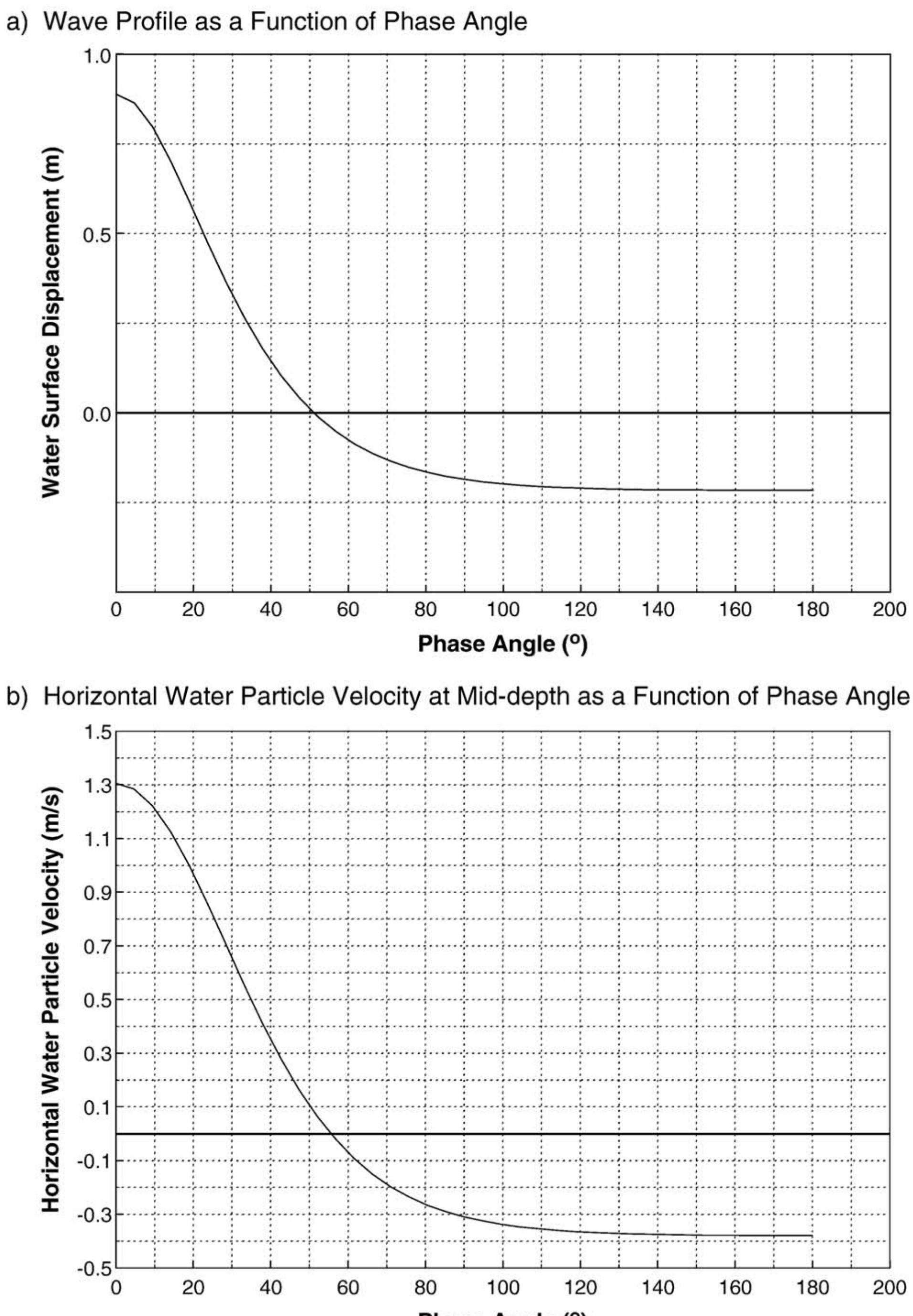

Fig. 5. Variation of wave profile (panel a) and horizontal water particle velocity at mid-depth (panel b), for example nonlinear wave.

4.2.3. Wave setup/setdown due to nonlinear wave propagation through vegetation

The nonlinear wave effects on setup due to wave energy dissipation by vegetation elements are quite different in character than for the case of linear waves examined earlier. In the linear case, as a result of the horizontal velocities being the same in magnitude but with opposite sign below trough and crest regions, all of the net force exerted by the vegetation on the water column originated above the wave trough level (Eq. (8)). For nonlinear waves, no such velocity antisymmetry exists and we can expect a net force on the vegetation to originate both below and above the trough level. For purposes here, we will illustrate the effect with a wave of the following characteristics

$$H = 1.1\text{m}, \quad T = 10.0\text{s}, \quad h = 3.0\text{m}$$

or

$$\begin{aligned} H/L_o &= 0.0071 \\ h/L_o &= 0.019 \end{aligned} \tag{21}$$

which is a wave of approximately one-half the breaking height and a h/L value of approximately 0.05, at the conventional shallow water limit. To illustrate the nonlinearity, the wave profile and velocity at mid-depth are presented in Fig. 5 where the larger values at the crest relative to those at the trough position are evident. The momentum gradients and forces are calculated over two depth ranges. For linear waves, the gradient in momentum flux is calculated over the vertical range from the bottom to mean water level (as per infinitesimally small waves) and over the range from the bottom to the instantaneous free surface. For nonlinear waves, the lower range is below the trough level and the upper range is the same as for linear waves. The force exerted on the vegetation is calculated over the range from the bottom to the trough level (yielding zero net force for linear waves) and from the bottom to the instantaneous free surface for both wave theories. For purposes of comparing linear and nonlinear quantities, dimensionless forces per unit area $(f)'$ and momentum flux gradients, $(\partial S_{xx}/\partial x)'$, are defined as

$$(f_x)' = \frac{f_x}{C_D \rho g D H^2/(2S^2)}. \tag{22}$$

and

$$(\partial S_{xx}/\partial x)' = \frac{(\partial S_{xx}/\partial x)}{C_D \rho g D H^2/(2S^2)}. \tag{23}$$

Table 1 summarizes these results where it is seen that for the linear wave theory case, the force reduces the wave setup by 73.3% of the value that would occur due to the same wave energy dissipation without the occurrence of a force (this result is based on integration of the energy dissipation to the mean water level). The nonlinear wave effects are substantial with the force being larger and of opposite sign of the momentum flux gradient. Thus the overall effect would be a *setdown* rather than a setup. For the nonlinear wave and quantities calculated over the full water column, the magnitude of the setdown would be 145% greater than the setup that would occur with the same energy dissipation without the occurrence of a force.

Table 1
Comparison of linear and nonlinear momentum flux gradients and forces due to waves propagating through vegetation

Property	Dimensionless momentum flux gradient, $(\partial S_{xx}/\partial x)'$ based on ε calculated from		Dimensionless force, $(f_x)'$	
	Bottom to mean free surface (linear waves) and bottom to trough level (nonlinear waves)	Bottom to instantaneous water surface	Bottom to trough level	Bottom to instantaneous water surface
Linear waves	−0.0277	−0.0378	0	−0.0203
Nonlinear waves	−0.0153	−0.0216	−0.0329	−0.0530

4.2.4. Wave setup/setdown due to bottom friction and nonlinear waves

The asymmetries of the near bottom water particle velocities about zero will cause an energy loss and a net force on the water column counter to the direction of wave propagation. As for the case of wave propagation through vegetation, this energy loss will cause a transfer of momentum and an associated wave setup/setdown. The same wave conditions are examined here as in the previous example.

The average shear stress, $\overline{\tau}_b$, on the bottom of the water column and energy dissipation per unit surface area, ε, are given by

$$\overline{\tau}_b = -\frac{\rho f}{8T} \int_t^{t+T} |u_b| u_b \, dt \tag{24}$$

and

$$\varepsilon = \frac{\rho f}{8T} \int_t^{t+T} |u_b| u_b^2 \, dt \tag{25}$$

where f is the Darcy–Weisbach friction coefficient and u_b is the bottom water particle velocity. Defining dimensionless quantities as before,

$$\left(\overline{\tau}_b\right)' = \frac{\overline{\tau}_b}{\rho g f H^2 k/8} = -0.0296 \tag{26}$$

and

$$(\partial S_{xx}/\partial x)' = \frac{(\partial S_{xx}/\partial x)}{\rho g f H^2 k/8} = -0.0135. \tag{27}$$

Thus, the effects of the average bottom shear stress would be greater than that of the wave energy dissipation and would result in a *setdown* rather than a setup. The magnitude of the setdown would be 119% greater than the wave setup that would result from the energy dissipation without the contribution of the net bottom shear stress. It is noted that the results found for the bottom shear stress for the nonlinear wave are fundamentally different than for the linear wave because the value of $\overline{\tau}_b$ for linear waves would be zero as calculated by Eq. (24) as done here for nonlinear waves.

5. Summary and conclusions

Wave setup can be considered as consisting of static and dynamic (oscillating) components. The static component is a result of transfer of wave related momentum to the water column as the wave breaks or dissipates energy by other mechanisms. Various features of the static setup component have been examined including effects of: beach slope, wave nonlinearities and energy dissipation resulting from internal drag forces caused by vegetation and surface forces due to bottom friction. The latter two have been considered for both linear and nonlinear waves with fundamentally different results. With linear waves propagating through vegetation, the only net drag force contribution is from above the trough level whereas, the non-sinusoidal velocities of the nonlinear waves result in net drag force components below and above the trough level. The bottom friction component for linear waves is due only to the streaming velocity since the linear bottom velocities are symmetric about zero. However, for the nonlinear waves, a net force occurs counter to the wave direction due to the asymmetry of the oscillatory bottom velocities. All analyses of internal and bottom forces with linear and nonlinear waves document that the resulting wave setup is substantially less than if the same energy loss were to occur without the presence of a force. For linear waves the setup due to vegetation and bottom friction damping was reduced by two-thirds relative to the same damping without the associated force. For the case of nonlinear waves examined, both the internal and bottom related energy losses and associated forces resulted in a net wave *setdown* rather than wave setup. Although to the authors' knowledge, some of the features examined here have not been demonstrated nor observed, they are soundly based in physics and of sufficient engineering relevance to warrant conducting laboratory and field experiments to quantify the extent to which they agree with theory.

Acknowledgements

This work was stimulated by projects funded under the Flood Insurance Program of the Federal Emergency Management Agency. The authors are indebted to J. A. Battjes and an anonymous reviewer for constructive comments and thorough reviews of an earlier version of this paper.

References

Battjes, J.A., 1972. Set-up due to irregular waves. Proceedings, ASCE, Proceedings 13th International Conference on Coastal Engineering, Vancouver, B. C., pp. 1992–2004.

Battjes, J.A., 1974. Computation of set-up, longshore currents, run-up and overtopping due to irregular waves, Ph.D. Thesis, Delft University of Technology. 244 pages.

Bowen, A.J, Inman, D.L., Simmons, V.P., 1968. Wave 'setup' and 'setdown'. Journal of Geophysical Research 73, 2569–2577.

Dalrymple, R.A., 1974. A finite amplitude wave on a linear shear current. Journal of Geophysical Research 79 (30), 4498–4504.

Davis, G.A., Nielsen, P., 1988. Field measurement of wave set-up. ASCE, Proceedings 23rd International Conference on Coastal Engineering, Malaga, Spain., pp. 539–552.

Dean, R.G., 1965. Stream function representation of nonlinear ocean waves. Journal of Geophysical Research 70 (18), 4561–4572.

Dean, R.G., 1974. Evaluation and development of water wave theories for engineering application, Vols. 1 and 2, Spec. Rep. 1. U.S. Army Coastal Engineering Research Center, Fort Belvoir, VA.

Dunn, S.L., Nielsen, P., 2000. Wave setup in rivers. ASCE International Conference on Coastal Engineering, Sydney, Australia, pp. 3432–3445.

Goda, Y., 1975. Irregular wave deformation in the surf zone. Coastal Engineering in Japan 18, 13–26.

Guza, R.T., Thornton, E.B., 1981. Wave set-up on a natural beach. Journal of Geophysical Research 96 (C2), 4133–4137.

Hansen, U.A., 1978. Wave setup and design water level. Journal of Waterway, Port, Coastal and Ocean Division, ASCE 104 (WW2), 227–240.

Hansen, J.B., Svendsen, I.A., 1979. Regular waves in shoaling water, experimental data. Institute of Hydrodynamics and Hydraulics Engineering, Series Paper, vol. 21.

Holman, R.A., 1990. Wave set-up Chapter 11, Volume 1. In: Herbich, J. (Ed.), Handbook of Coastal and Ocean Engineering., pp. 635–646.

Holman, R.A., Sallenger, A.H., 1985. Setup and swash on a natural beach. Journal of Geophysical Research 90 (C1), 945–953.

James, I.D., 1974. Non-linear waves in the nearshore region: shoaling and setup. Estuarine and Marine Coastal Science 2, 207–234.

Lentz, S., Raubenheimer, B., 1999. Field observations of wave setup. Journal of Geophysical Research 104 (C11), 25867–25875.

Longuet-Higgins, M.S., 1973. The mechanics of the surf zone. Proceedings, 13th International Congress on Theoretical and Applied Mechanics. Springer Verlag, pp. 213–228.

Longuet-Higgins, M.S., Stewart, R.W., 1960. Changes in the form of short gravity waves on long waves and tidal currents. Journal of Fluid Mechanics 8, 565–583.

Longuet-Higgins, M.S., Stewart, R.W., 1962. Radiation stress and mass transport in gravity waves with application to surf beat. Journal of Fluid Mechanics 13, 481–504.

Longuet-Higgins, M.S., Stewart, R.W., 1963. A note on wave setup. Journal of Marine Research 21 (4), 4–10.

Longuet-Higgins, M.S., Stewart, R.W., 1964. Radiation stresses in water waves; a physical discussion with application. Deep Sea Research 11, 529–540.

Munk, W.H., 1949. Surf beats. Transactions of the American Geophysical Union 30, 849–854.

Nelson, R.C., 1993. Depth limited design wave heights in very flat regions. Coastal Engineering 23, 43–59.

Nielsen, P., 1989. Wave setup and runup: an integrated approach. Coastal Engineering 13, 1–9.

Phillips, O.M., 1966. The Dynamics of the Upper Ocean. Cambridge University Press, Cambridge.

Raubenheimer, B., Guza, R.T., Elgar, S., 2001. Field observations of setdown and setup. Journal of Geophysical Research 106, 4629–4638.

Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J., Beach, R.A., 2001. Wave runup, extreme water levels and the erosion of properties backing beaches. Journal of Coastal Research 17 (2), 407–419.

Stive, M.J.F., Wind, H.G. (1982) A Study of Radiation Stress and Set-up in the Nearshore Zone, Publication No. 267, Waterlopkundig Laboratorium, Delft Hydraulics Laboratory. 25 Pages.

Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger Jr., A.H., 2004. Empirical Parameterization of Setup, Swash, and Runup. Manuscript Submitted to Journal of Geophysical Research for Publication Consideration.

Svendsen, I.A., 1984. Wave heights and set-up in a surf zone. Coastal Engineering 8, 302–329.

Svendsen, I.A., Hansen, J.B., 1976. Deformation up to breaking of periodic waves on a beach. ASCE, Proceedings, 15th International Conference on Coastal Engineering. ASCE, pp. 477–496.

Svendsen, I.A., Madsen, P.A., Hansen, J.B., 1978. Wave characteristics in the surf zone. ASCE, Proceedings, 16th International Conference on Coastal Engineering. ASCE, pp. 520–539.

Tucker, M.J., 1950. Surf beats: waves of 1 to 5 minutes period. Proceedings of the Royal Society of London, Series A 202, 565–573.