Ocean Engineering 55 (2012) 52–61

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

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

Near-shore wave induced setup along Kalpakkam coast during an extreme cyclone event in the Bay of Bengal

Sashikant Nayak [b], Prasad K. Bhaskaran [b,*], R. Venkatesan [a]

[a] Radiological Safety Division, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, India
[b] Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology Kharagpur, Kharagpur 721 302, India

ARTICLE INFO

Article history:
Received 9 February 2012
Accepted 28 July 2012
Available online 16 August 2012

Keywords:
Radiation stress
Wave setup
Sensitivity experiments
NARGIS cyclone

ABSTRACT

An enhanced sea level during an extreme weather event can result from cumulative effects of reduced sea-level pressure, storm surge, tidal effects and wave induced setup. A numerical experiment was conducted to evaluate sensitivity of model resolution and bottom slope on wave induced setup for an arbitrary coast. Further, an assessment of wave setup at coastal Kalpakkam was investigated, in response to passage of a Category-4 cyclone 'NARGIS', in the central Bay of Bengal. The sensitivity experiments cover an arbitrary region of 5 km × 5 km, with varying horizontal resolutions and beach slopes, and subjected to uniform wind forcing and JONSWAP wave spectra prescribed at the open boundary. The computed wave setup using SWAN model reveals that model resolution is not sensitive for gentle bottom slopes, unlike the case with steep bottom slopes. Findings from sensitivity experiments were then applied to evaluate wave setup at three different locations along Kalpakkam coast, for the Cyclone NARGIS event. The study shows that wave setup was highest for a steep slope (1:20), reducing to almost 50% for gentle slopes (1:80). It is inferred that wave setup is an important parameter that needs to be incorporated in an operational storm surge forecasting system.

1. Introduction

Wave setup is a coastal phenomena linked with an increased water level in the near-shore region, arising due to the transfer of wave momentum to underlying water column during the wave breaking process. This leads to a transient rise and fall of mean water level in the surf zone, technically referred to as 'wave setup' and 'wave set-down'. The resultant variation in mean water level can thus be attributed to the variations in wave radiation stress. In order to explain the setup and set-down processes in near-shore areas, a precise knowledge of wave radiation stress is an essential pre-requisite. The prediction of wave setup in near-shore regions is critical, especially during extreme events, where the net water level arises due to cumulative effects from reduced sea-level pressure, storm surge, tidal effects and wave induced setup. Advanced knowledge of wave setup process in near-shore regions has diverse practical applications in ocean engineering discipline. This information of net water level is vital in the design aspects of coastal and near-shore structures, where significant flooding and oscillating water levels, resulting from extreme events, can pose significant threat to the long term stability of these structures.

A scientific format for establishing the static and fluctuating water level characteristics in near-shore areas, which includes wave setup, run-up and associated overtopping on sandy beaches and natural barriers is documented in the guidelines and specifications for flood hazard mapping partners (Dean et al., 2005). A more recent study on numerical modeling, pertaining to the evolution of beach topography arising from waves and currents with special emphasis on coastal structures, is reported in Nam (2010). That study suggests that surface roller (waves) plays an important role in the generation of near-shore currents. The concept of roller was first theoretically introduced by Svendsen (1984a,b) to enhance the modeling of wave setup and undertow in the surf zone. Later, the roller model, which includes the roller energy gradients in the energy flux balance, were employed in many near-shore studies relevant to wave induced currents (Ruessink et al., 2001; Tajima and Madsen, 2006; Roelvink et al., 2010).

An analytical theory for wave setup and set-down, induced by obliquely incident waves on impermeable beach profile, due to distant swells, is reported in Hsu et al. (2006). Their study suggests that wave setup and set-down would decrease when wave obliquity is increased. The theory is primarily applicable to spilling and plunging breakers across the surf zone, within which wave amplitude is assumed to be linearly related to the local water depth.

In a recent study, measurements were conducted for wave setup at Ipan, a fringing reef on the south-east coast of Island Guam located in the Pacific by Vetter et al. (2010). They examined

* Corresponding author. Tel.: +91 3222 283772; fax: +91 3222 255303.
E-mail addresses: prasadlsu@yahoo.com, pkbhaskaran@naval.iitkgp.ernet.in (P.K. Bhaskaran).

0029-8018/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2012.07.036

the relationship between incident waves and wave driven setup during storm and non-stormy conditions. The study demonstrated that predictions based on the traditional wave setup theory and idealized model for localized wave breaking along forward face of the reef was in agreement with observations. Their study focused on a steeply sloping sandy beach, where wave setup was about 35% of the incident root mean square wave height at 8 m water depth. An increase of about 10% in setup was observed and reported during extreme wave events at this location.

The subsequent sections highlight the implementation of SWAN wave model; the importance of wave radiation stress and computational details of wave induced setup; the methodology used in planning the sensitivity experiments and computation of wave setup for the NARGIS cyclone; followed by the results and discussion on the near-shore wave induced setup computed for the Kalpakkam coast, located along the east coast of India.

2. The SWAN wave model

The SWAN (Simulating Waves Nearshore) model (Booij et al., 1999) is a third generation wave prediction model based on the wave action balance equation, which can be mathematically expressed in the form

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}(c_xN)+\frac{\partial}{\partial y}(c_yN)+\frac{\partial}{\partial \sigma}(c_\sigma N)+\frac{\partial}{\partial \theta}(c_\theta N) = \frac{S_{total}}{\sigma} \equiv \frac{S_{in}+S_{nl}+S_{ds}+S_{bot}}{\sigma} \quad (1)$$

where, $N(\sigma,\theta)$ is the wave action density, equivalent to the wave energy density $E(\sigma,\theta)$divided by the intrinsic frequency (σ). The other terms in Eq. (1) denotes the time (t), relative frequency(σ), the wave direction (θ), the propagation velocities in the x- and y-spaces (c_x and c_y) respectively; the terms c_σ and c_θ are the propagation velocities in spectral space and direction. In other words, the first term in the above equation represents the local rate of change of action density in time. The second and third terms denote the propagation of action density in geographical space. The fourth term represents the shifting of action density in frequency space due to variations in depth and currents. The fifth term takes care of the depth and current induced refraction processes. The terms on the right hand side of the action density balance equation (S_{total}) account for the resultant action density attributed from wave generation (S_{in}); non-linear wave–wave interactions (S_{nl}) and dissipation mechanisms (S_{ds}) and (S_{bot}). These terms refer to the source and sink mechanisms in the wave energy balance equation. The wave generation term S_{in} deals with the momentum transfer from atmosphere to ocean and responsible for wave evolution and growth during the initial stage of wave growth. The weak resonant non-linear wave–wave interaction responsible for the re-distribution of wave energy is represented by the S_{nl} term. The dissipative effects due to white-capping, bottom effects and depth induced breaking are represented by the terms S_{ds} and S_{bot} respectively. A detailed description on physical parameterization of these source and sink mechanisms can be found in Ris (1997), Ris et al. (1999) and Booij et al. (1999).

3. Wave radiation stress

The earliest study on radiation stress was attempted in the late 1950s and it was called by the name 'wave thrust' (Lundgren, 1963). Thereafter, pioneering work on this topic was conducted by Longuet-Higgins and Stewart (1960, 1962, 1964), who introduced the name of 'radiation stress', for excess flux of horizontal momentum due to the presence of waves. In a coastal environment, the alongshore variation of radiation stress, effected from shoaling and breaking of waves, is mass balanced by slope in the mean water level. The prediction of wave setup using linear sinusoid waves was based on the assumption that waves in surf zone maintain a constant proportionality ratio of 0.32 between wave height and corresponding water depth (Longuet-Higgins and Stewart, 1964). The Bowen's (1969) model predicted a linear profile of mean water level as a function of water depth. However, a series of laboratory and field measurements proved that the paradigm of linear profile is invalid. The shortcoming in Bowen's model was due to the assumption that wave height to water depth ratio (γ) was taken constant along the surf zone. The recent studies by Raubenheimer et al. (1996) and Power et al. (2010) reported that the assumptions of Bowen, concerning the breaker parameters, stand invalid. In this context, Raubenheimer et al. (2001) and Yemm (2004) assumed shoreward increasing nature of γ in mean water level calculations. Their study simultaneously measured and predicted the wave setup using sinusoid wave radiation stress formulation. The influence of non-sinusoid wave shape on radiation stress in surf zone and their importance in mean water level predictions was investigated by Svendsen (1984a). He assumed a non-sinusoidal, but linear wave profile in the radiation stress formulation. The essence from the above stated works means that the near-shore wave setup has a direct bearing on the proportionality constant (γ). The radiation stress can be expressed in terms of the two dimensional wave energy spectrum of the surface elevation. The surf zone associated with wave setup is quite dynamic due to strong non-linearity and also due to rapid transformation of an organized wave motion into a turbulent one. Hence, the radiation stress can be expressed as wave induced momentum flux averaged over a given time interval. The variations of radiation stress and mean water level for a two-dimensional shoaling and breaking of progressive, periodic waves on a plane and gently sloping laboratory beach was investigated by Stive and Wind (1982). A theoretical model for wave height and setup in the surf zone using time averaged equations of energy and momentum flux, radiation stress and energy dissipation which include the actual shape of waves was reported by Svendsen.

3.1. Computation of wave radiation stress

The linearized form of equation for radiation stress can be mathematically expressed as

$$\frac{dS_{xx}}{dx}+\rho gh\frac{d\overline{\eta}}{dx}=0 \quad (2)$$

where, the term 'h' is the total water depth and η is the mean surface elevation including the wave induced setup. The radiation stress tensor can be expressed as

$$S_{xx}=\rho g\iint\left[n\cos^2\theta+n-\tfrac{1}{2}\right]Ed\sigma d\theta \quad (3)$$

where, $n=c_g/c_p$ (c_g and c_p being the group velocity and wave celerity respectively). Based on observations and computations of the vertically integrated momentum balance equation (Dingemans, 1987), the wave induced currents are driven by divergence free part of wave forces, whereas the wave setup is due to the rotation free part of these forces. Hence, the wave induced setup in a two-dimensional case can be calculated using the divergence of the momentum balance equation.

4. Methodology

To estimate the water level rise due to wave setup, the SWAN wave model (Booij et al., 1999), a third generation wave prediction model was used in the present study. The model computes the random, short crested wind waves in coastal regions. The momentum