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An empirical formula for maximum wave setup based on a coupled wave-current model

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ABSTRACT

The present paper proposes an empirical formula for maximum wave setup based on a coupled wave-current model. The wave model is the Simulating Waves Nearshore (SWAN) model; the current model is the Finite Volume Community Ocean Model (FVCOM). This study first evaluates the coupled model system against mean water level data collected from a series of laboratory and field experiments. The model calculation agrees with the measurements. Then, the study uses the model results from simulations with a range of wave conditions to develop an empirical formula for the maximum wave setup as a function of wave height, wavelength in deep water, and beach slope. The formula agrees with experimental and *in situ* measurements and shows better performance than previous formulas.

1. Introduction

Wave setup (or setdown), defined as an increase (or decrease) in the mean water level with the presence of waves, is a common dynamic process in the nearshore zone (Lentz and Raubenheimer, 1999). Wave setup dynamics is important for understanding many coastal phenomena, such as sediment transport and wave-structure interaction (Calabrese et al., 2008; Hu et al., 2009). The maximum wave setup elevation is a key criterion for coastal protection and coastal flooding prediction (Guza and Thornton, 1981; Nielsen, 1988).

Since the mid-20th century, researchers have investigated wave setup using theoretical, experimental and numerical methods. Considering the radiation stress caused by regular waves, e.g., Longuet-Higgins and Stewart (1964, hereinafter LHS) derived an analytical solution for the horizontal gradient of the mean sea level along the offshore direction:

$$\frac{d\eta}{dx} = -K\tan\beta, \quad K = \frac{1}{1+8/3\gamma_b^2} \tag{1}$$

where η is the mean water level, x is the offshore coordinate, β represents the angle of the beach slope, and γ_b is the ratio of wave height-to-water depth at breaking and is assumed to be constant. With the assumption that $\beta =$ constant and the solution of Eq. (1), Battjes (1974) showed that the maximum wave setup value would occur on a beach characterized by the following expression:

$$\eta_{\max} = \frac{5}{16}\gamma_b H_b \tag{2}$$

where H_b is the wave height at the breaking line.

Based on laboratory experiments, Bowen et al. (1968) and Van Dorn (1976) studied the maximum setup properties of monochromatic waves with wave flumes, and they found that the LHS theory agreed with their experiments. Battjes (1972, 1974) investigated the wave setup of random waves using laboratory experiments. They concluded that the maximum setup was somewhat lower than that predicted by the LHS theory, most likely because the theory ignored variation in γ_b. Since then, several studies have produced field observations (e.g., Guza and Thornton, 1981; Nielsen, 1988; Raubenheimer et al., 2001; Stockdon et al., 2006). Based on *in situ* data from natural, gently sloping beaches in southern California, Guza and Thornton (1981) proposed the following expression of the maximum mean water level:

$$\eta_{\max} = 0.17H_{0,s} \tag{3}$$

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where $H_{0,s}$ is the significant wave height (the average height of the highest one-third of waves or four times the standard deviation of the time series of sea-surface elevation) in deep water. Later studies extended Eq. (3) to a more general relationship including the Iribarren number (Nielsen, 1988; Stockdon et al., 2006):

$$\eta_{\max} \propto H_{0,s}\xi_0 \tag{4}$$

in which $\xi_0 = \tan\beta/\sqrt{H_{0,s}/L_0}$ is the Iribarren number and L_0 is the wavelength in deep water obtained using the peak wave period. Holman and Sallenger (1985) reported an empirical regression equation for the maximum setup value based on the data collected by field experiments under middle tide conditions:

$$\frac{\eta_{\max}}{H_{0,s}} = 0.46\xi_0 \tag{5}$$

Hanslow and Nielsen (1992) produced the following empirical equation based on field measurements along the New South Wales coast:

$$\eta_{\max} = 0.048(H_{0,rms}L_{0,s})^{0.5} \tag{6}$$

where $H_{0,rms}$ is the root mean square wave height in deep water and $L_{0,s}$ is the wavelength in deep water computed using the significant period (the average period of the highest one-third of waves). The wave heights are assumed to obey the Rayleigh distribution in deep water, indicating that $H_{0,rms} = H_{0,s}/\sqrt{2}$ (Battjes and Groenendijk, 2000). Using datasets from ten field experiments over a range of beach and wave conditions, Stockdon et al. (2006) developed an empirical formulation for the maximum wave setup using an Iribarren-like form:

$$\eta_{\max} = 0.35\tan\beta(H_{0,s}L_0)^{0.5} \tag{7}$$

Although researchers have presented expressions of the maximum wave setup for both monochromatic and random waves, most of the expressions for random waves are empirical formulas fitted to field observation data collected from limited places and times. Therefore, studies have yet to explore the broad applicability of these formulas.

Recently, researchers have increasingly used numerical models to simulate wave dynamics in idealized or realistic situations. For instance, Wolf et al. (1988) developed a coupled model to investigate the interactions between waves and tides or surges. Schäffer et al. (1993) and Madsen et al. (1997a, 1997b) simulated wave dynamics in the surf zone using a Boussinesq-type model and obtained good agreement between the model results and measurements. More recently, Mellor et al. (2008) developed a coupled wave-circulation model to consider the influences of wave-induced radiation stress on ocean circulation. Warner et al. (2008) developed a coupled wave-current-sediment model to stress the role of waves on sediment transport in estuaries and coastal waters. Kumar et al. (2012) implemented vortex force formalism in the coupled ocean-atmosphere-wave-sediment transport modeling system (COAWST). Numerical models involve solving variations in wave parameters with time and space via a set of momentum and energy conservation equations with forcing, boundary and initial conditions. In contrast to field observations, where forcing conditions are complex, researchers can use numerical models to study wave dynamics under controlled forcing conditions based on specific purposes. Accordingly, this study investigates maximum wave setup using a coupled wave-current model.

The arrangement of the present paper is as follows. Section 2 describes the model setup and verification. Section 3 presents the model results and an empirical formula for the maximum wave setup. Section 4 shows the evaluation of this formula. Section 5 provides a discussion of the limitations of this approach and comparisons between this empirical formula and several previous formulations. Finally, Section 6 presents the conclusions.

2. Model description

2.1. Model framework

The present study applies a coupled wave-current model system that includes the Simulating Waves Nearshore (SWAN) wave model and the Finite Volume Community Ocean Model (FVCOM) circulation model. Information exchange between the two models uses Model-Coupling Toolkit (MCT) software (Jacob et al., 2005; Larson et al., 2005). The present investigation uses MCT to couple SWAN and FVCOM following the method of Yang (2012) and runs the two models on the same unstructured grid. Both SWAN and FVCOM run on their set of processors in the coupled system and exchange information based on a defined time interval depending on computational power and the temporal scales of the specific wave and circulation conditions. Fig. 1 shows the information exchange between SWAN and FVCOM. The coupled model system runs on Linux platforms. FVCOM uses the wave parameters transferred from SWAN to calculate the force in the form of wave-induced radiation stress gradients and to generate the currents and wave setup. SWAN uses the currents and water levels transferred from FVCOM to include current and water level change effects on wave transformation and breaking processes. Finally, the wave setup is numerically established after reaching a steady state. The maximum wave setup is defined as the mean water level elevation at the interaction between wetting and drying on the beach face. In the model run, the minimum grid spacing is 1/7 to 1/20 of the shoreline advancement landward in the horizontal direction and is small enough to be suitably accurate for the maximum setup.

2.2. Wave model

SWAN is a third-generation wave model developed by Delft University and is a fully discrete spectral model based on the action balance equation (Booij et al., 1999). The mean rate of energy dissipation per unit horizontal area as a result of wave breaking uses the results of Battjes and Janssen (1978) based on the following expression:

$$D_{tot} = -\frac{1}{4}\alpha_{BJ}Q_b\left(\frac{\overline{\sigma}}{2\pi}\right)H_{\max}^2 \tag{8}$$

where the coefficient $\alpha_{BJ} = 1$, $\overline{\sigma}$ is the mean frequency, and Q_b is the fraction of breaking waves and is computed as follows:

$$\frac{1-Q_b}{\ln Q_b} = -8\frac{E_{tot}}{H_{\max}^2} \tag{9}$$

where E_{tot} is the total wave energy. The maximum wave height $H_{\max}$ is determined in SWAN via $H_{\max} = \gamma_b d$, in which γ_b is the breaker index and

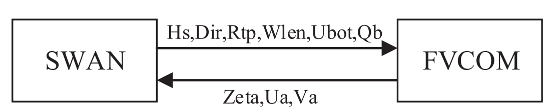

Fig. 1. Information exchange between model components. SWAN provides wave parameters, including significant wave height (Hs), wave direction (Dir), peak wave period (Rtp), wavelength (Wlen), bottom orbital velocity (Ubot) and fraction of breaking waves (Qb), to FVCOM. FVCOM provides water elevation (Zeta) and depth-averaged current fields (Ua and Va) to SWAN.

Table 1
Experimental conditions employed.

Literature	Wave type	H_{rms} (m)	D (m)	T_p (sec)	tanβ	θ
Stive (1985)	Random	1.00	4.19	5.41	1:40	0°
Ting (2001)	Random	0.22	0.46	2.00	1:35	0°
Shen (2015)	Random	0.026	0.18	1.50	1:100	30°
Scott et al. (2004)	Random	0.76	0.42	4.00	Non-uniform	0°