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Modelling Nonlinear Near-Bed Orbital Velocity in the Shallow Water

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Abstract: A model for nonlinear near-bed orbital velocity in shallow water was developed. The equations proposed by Isobe and Horikawa (1982) to calculate the near-bed peak onshore and offshore orbital velocities in the nearshore were modified in order to achieve more accurate predictions. Based on field data from Egmond Beach in the Netherlands, the correction coefficient and maximum skewness were determined as functions of the Ursell number. The model was validated against several different data sets collected during small-scale laboratory experiments at Delft University of Technology, large-scale laboratory experiments in the Delta flume of Delft Hydraulics, and field campaigns at Egmond beach. The validation showed that the model reproduced well the measurements from both the laboratory and the field.

Keywords: velocity skewness, velocity asymmetry, orbital velocity, wave non-linearity, sediment transport

1 Introduction

Research on velocity skewness plays a key role in sediment transport and beach morphological change in shallow water, especially for the cross-shore transport. The difference between the onshore and offshore velocities during a wave cycle often generates onshore-directed transport (Ribberink and Al-Salem, 1994; O'Donoghue and Wright, 2004; Ruessink et al., 2011), contributing to the local beach morphological evolution. The net transport induced by velocity skewness and undertow is one of the main factors to form nearshore bars in shallow water (Grasmeijer and Van Rijn, 1998; Elfrink et al., 1999; Doering et al., 2000; Van Rijn et al., 2003; Elfrink et al., 2006; Ruessink et al., 2007). Furthermore, the transport rates strongly depend on the current velocity, approximately to the third power of velocities (Van Rijn, 2007a and b). Therefore, an accurate prediction of the near-bed orbital velocities in shallow water is required when calculating sediment transport and morphological change.

Several numerical models based on the Boussinesq equations were developed that could reasonably well reproduce measurements of time-varying orbital velocities and skewness through the shoaling region. However, predictions of skewness at breaking and in the surf zone were significant different from the measurements (Elgar et al., 1990; Madsen et al., 1997; Tissier et al., 2012). Furthermore, such advanced numerical models require fine resolution in both time and space, resulting in the need for significant computational resources. Therefore, their applications are often only suitable for small coastal areas and short-term simulations.

Another approach for determining the velocity skewness the use of semi-empirical formulas. The advantage of this approach is its simplicity and robustness compared to the aforementioned numerical models, making it suitable for application to large coastal areas. Significant progress was made several decades ago concerning the prediction of velocity skewness in the shallow water (Isobe and Horikawa, 1982; Grasmeijer and Ruessink, 2003; Elfrink et al., 2006; Abreu et al., 2010; Ruessink et al., 2012). However, the discrepancy between calculations and observations are still large at the breakpoint and in shallow water (Elfrink et al., 2006, Rocha et al., 2017). Thus, modifications of the formulas are needed to improve the prediction of velocity skewness, which in turn will yield more reliable sediment transport estimations in the shallow water.

The overall aim of this study is to improve the calculation of nonlinear near-bed orbital velocity in shallow water. In order to achieve this objective, a numerical model was developed, calibrated, and validated to calculate the near-bed orbital velocities in the nearshore under a wide range of wave conditions. The model includes two sub-models: (i) a nearshore random wave transformation model (Mase, 2001; Nam et al. 2009, 2017), and (ii) a nonlinear near-bed orbital velocity model (Isobe and Horikawa, 1982; Grasmeijer and Ruessink, 2003). Based on measurements collected at Egmond Beach in the Netherlands (Ruessink et al., 2000 and 2001; Kleinhout, 2000), the correction coefficient and maximum skewness in the formulas of Isobe and Horikawa (1982) were modified with regard to the Ursell number, producing more accurate results for the peak onshore and offshore orbital velocities.

The model was then validated against several data sets collected from small-scale laboratory experiments at Delft University of Technology (Grasmeijer and Van Rijn, 1999), large-scale laboratory experiments in the Delta flume of Delft Hydraulics (Roelvink and Reniers, 1995), and field campaigns at Egmond beach (Ruessink et al., 2001; Kleinhout, 2000). In general, the model reproduced well the measurements from both the laboratory and the field. The model is expected to produce more accurate and reliable sediment transport estimates over a wave cycle, which can be applied to compute beach morphological evolution.

2 Model Descriptions

2.1 Nearshore random wave transformation

A multi-directional and frequency random wave transformation model was developed by Mase (2001). Nam et al. (2009 and 2017) modified the model in order to obtain more accurate prediction of wave transformation in the surf zone. The governing equation for steady state is expressed as follows,

$$\frac{\partial(v_x S)}{\partial x}+\frac{\partial(v_y S)}{\partial y}+\frac{\partial(v_\theta S)}{\partial \theta}=\frac{\kappa}{2\omega}\left\{\left(CC_g\cos^2\theta S_y\right)_y-\frac{1}{2}CC_g\cos^2\theta S_{yy}\right\}-\frac{K}{h}C_g S\left\{1-\left(\frac{\Gamma h}{H_s}\right)^2\right\} \quad (1)$$

where S = angular-frequency spectrum density, (x, y) = horizontal coordinates, θ = angle measured counterclockwise from the x axis, κ = free parameter, ω = wave frequency, C = phase speed, and C_g = group speed, (v_x, v_y, v_θ)= propagation velocities in their respective coordinate directions, h = still water depth, K= decay coefficient, Γ = stable coefficient, and H_s = significant wave height.

The decay and stable wave height coefficients play a key role in calculating the energy dissipation. These coefficients are determined (Nam et al., 2017) as,

$$\Gamma = 0.45+\beta,\ K=\frac{0.9}{8}\left(1+\frac{\beta}{\sqrt{H_o/L_o}}\right) \quad (2)$$

where β = bottom slope, H_o = offshore wave height, and L_o = offshore wave length.

The output of the model includes three main parameters: significant wave height H_s, significant wave period T_s, and mean wave direction $\overline{\theta}$ (Mase, 2001, Nam et al., 2009 and 2017), determined from the spectrum.

2.2 Nonlinear near-bed orbital velocity

Isobe and Horikawa (1982) derived a method to calculate the nonlinear near-bed orbital velocity based on fifth-order Stokes wave theory and third-order cnoidal wave theory. The full amplitude of the near-bed orbital velocity (Fig. 1) is determined as,

$$\hat{u} = 2rU_w \quad (3)$$

where r = correction coefficient, U_w = near-bed horizontal orbital velocity amplitude using linear wave theory.

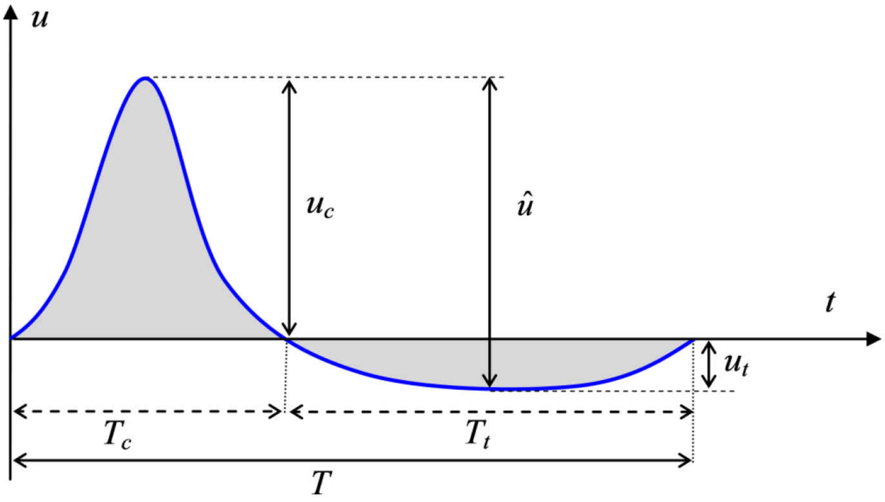

Fig. 1. Definitions of variables for an asymmetric velocity profile.

The correction coefficient can be determined based on the laboratory and field data. In the study of Isobe and Horikawa (1982), the coefficient depends on the local water depth, offshore wavelength, and offshore wave height. Grasmeijer and Ruessink (2003) modified the correction coefficient so that it depends on the local significant wave height and water depth. In the present paper, based on the field data collected at Egmond beach, the coefficient is dependent on the Ursell number (Fig. 2) according to the following fitting function

$$r = p_1 \log(U_r) + p_2 \tag{4}$$

where U_r = Ursell number, p_1 and p_2= best fit coefficients. Eq. (4) is valid for the Ursell numbers in the range between 5 and 760.

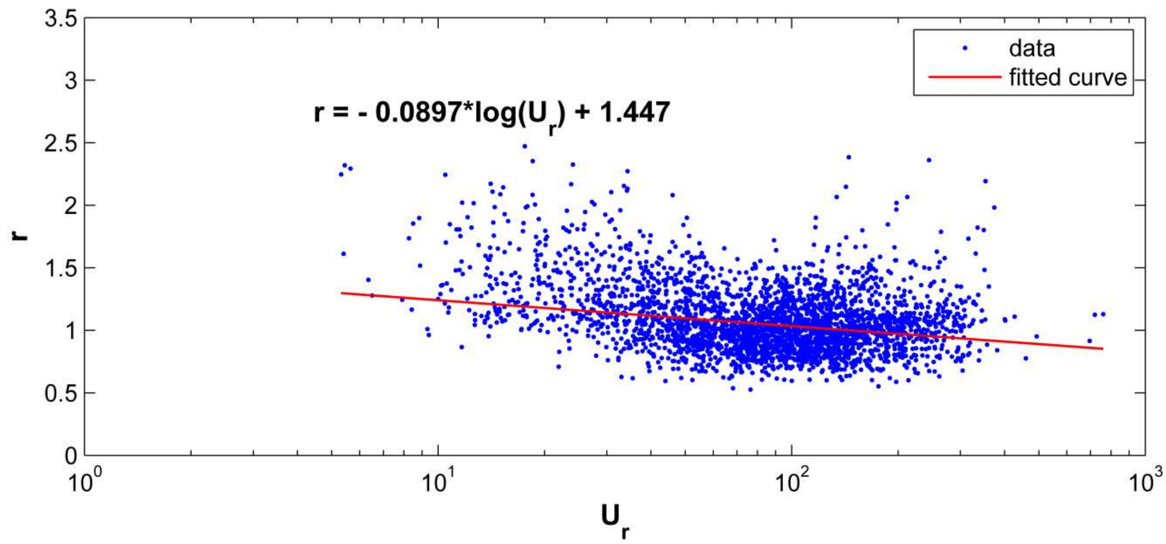

Fig. 2. Relationship between correction coefficient and Ursell number.

The Ursell number is calculated as,

$$U_r = \frac{H_s L^2}{d^3} \tag{5}$$

where L = local wavelength.

Using a robust linear least-square fitting method, the best fit coefficients values are determined as,

$$p_1 = -0.0897 \pm 0.0038 \ , \ p_2 = 1.447 \pm 0.017 \tag{6}$$

with the $\pm$ values representing the 95% confidence limits.

The near-bed peak onshore orbital velocity (u_c) is calculated following the approach of Isobe and Horikawa (1982), based on a parameterization of fifth-order Stokes wave theory and third-order cnoidal wave theory in which the deformation of the velocity profile due to bottom slope was included as,

$$\left(\frac{u_c}{\hat{u}}\right) = 0.5 + \left(\left(\frac{u_c}{\hat{u}}\right)_{\max} - 0.5\right)\tanh\left(\frac{(u_c/\hat{u})_a - 0.5}{(u_c/\hat{u})_{\max} - 0.5}\right) \tag{7}$$

where $\left(\frac{u_c}{\hat{u}}\right)_{\max}$ is the maximum skewness and $\left(\frac{u_c}{\hat{u}}\right)_a$ is calculated as

$$\left(\frac{u_c}{\hat{u}}\right)_a = \lambda_1 + \lambda_2 \frac{\hat{u}}{\sqrt{gd}} + \lambda_3 \exp\left(-\lambda_4 \frac{\hat{u}}{\sqrt{gd}}\right) \tag{8}$$

with g = acceleration due to gravity, λ_i (i =1 to 4) = empirical parameters depend on the wave period, water depth, and acceleration due to gravity (Isobe and Horikawa, 1982; Grasmeijer and Ruessink, 2003).

In the original formulas, Isobe and Horikawa (1982) determined the maximum skewness based on the beach slope. However, this calculation is not valid when the beach slope is very small and close to zero. Grasmeijer and Ruessink (2003) claimed that the influence of slope on the maximum skewness is negligible. Thus, they modified the maximum skewness so that it depends on the water depth and wavelength. Nevertheless, the predicted values of the maximum skewness were significantly larger than the measured values for the field data, implying an overestimation in the calculations.

In the present study, the maximum skewness is determined based on the Ursell number (Fig. 3) as,

$$\left(\frac{u_c}{\hat{u}}\right)_{\max} = 0.0235\ \log(U_r) + 0.552 \tag{9}$$

This expression is more general than the previous formulas, and can be applied for a wide range of wave conditions. For the Egmond Beach, the maximum skewness based on Eq. (9) varied from 0.59 to 0.71.

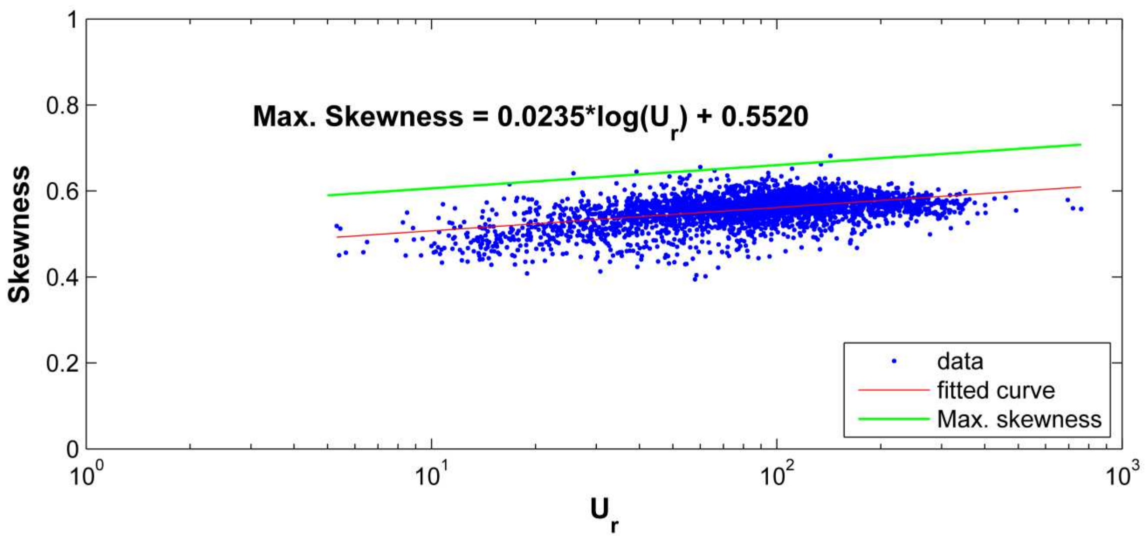

Fig. 3. Relationship between skewness and Ursell number.

The near-bed peak offshore orbital velocity (u_t) is determined as,

$$u_t = \hat{u} - u_c \tag{10}$$

3 Model Validation

3.1 Small-scale laboratory data from Delft University

The test series B1 and B2were carried in the wave flume of the Delft University of Technology (Grasmeijer and Van Rijn, 1999) under irregular waves with the incoming significant wave height of 0.16 m and 0.19 m, respectively, and the peak wave period of 2.3 s. The model beach with an artificial longshore bar was constructed in the flume by sand with a median grain size of 0.095 mm (Fig. 4d). In the present paper, the test B2 was employed to validate the model.

Fig. 4 shows the comparison between the calculations of significant wave height (a), peak onshore orbital velocity (b), and peak offshore orbital velocity (c) for measurements at 10 locations. As can be seen, the calculated significant wave height agreed well with measurements. The rms error between measurements and calculations of the significant wave height is approximately 5.2 %.The calculations of peak onshore orbital velocity are also in very good agreement with measurements, although some underestimation of the measurements occurs at the crest of sandbar. The rms error for the peak onshore velocity is about 8.7 %. For the peak offshore orbital velocity, the predictions also underestimate the measurements at the offshore locations on the sandbar. However, at other locations in the vicinity of the sandbar, the calculations agreed well with measurements. The rms error for the peak offshore velocity is relatively higher than for the peak onshore velocity, and equals to 15.6 %. The obtained higher value on the rms error is mainly due to the discrepancy between the calculations and measurements offshore of the sandbar.

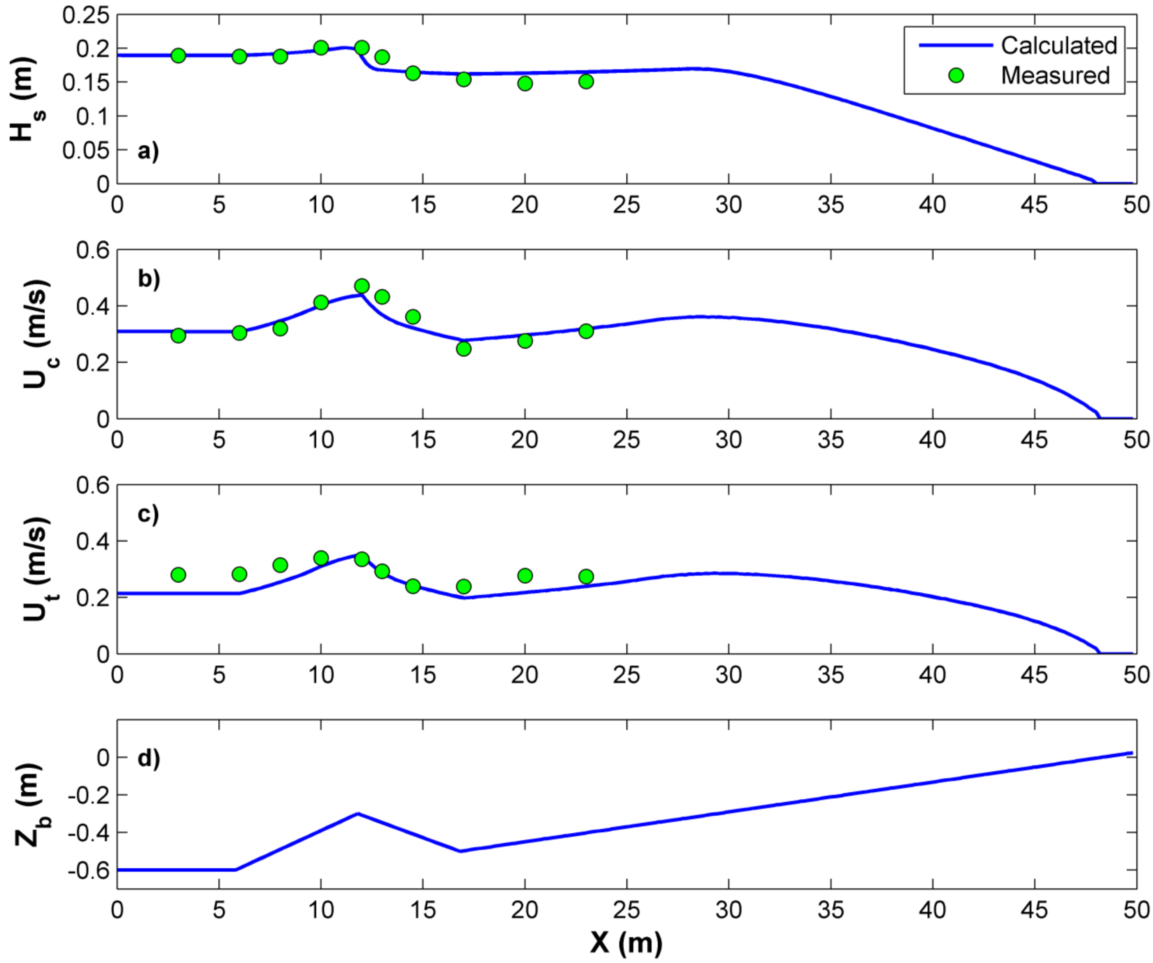

Fig. 4. Comparisons between calculated significant wave height (a), peak onshore (b) and offshore (c) orbital velocities with measurements for test B2 (Grasmejer and Van Rijn, 1999) together with the profile shape.

3.2 Large-scale laboratory data LIP-1D from Delta flume

Data sets from the Test 1B, including the significant wave height, peak onshore and offshore velocities, were employed to validate the model. Highly erosive wave conditions were generated for this test with an incoming significant wave height of 1.4 m and a peak wave period of 5 s. The model beach in the flume was designed as an equilibrium profile with fine sand having a median grain size of 0.22 mm.

As can be seen in Fig. 5, the calculations of significant wave height, peak onshore and offshore velocities are in very good agreement with the measurements. The prediction of significant wave height agreed well with measurements at all 10 locations. Thus, the rms error for significant wave height is relative small, approximately 6.1 %. For the near-bed peak onshore and offshore orbital velocities, the calculations somewhat underestimated the measurements in the surf zone, especially at x = 160 m (Fig. 5b and c). The rms errors for both onshore and offshore velocities are quite similar, approximately 16.4 % and 16.2 %, respectively.

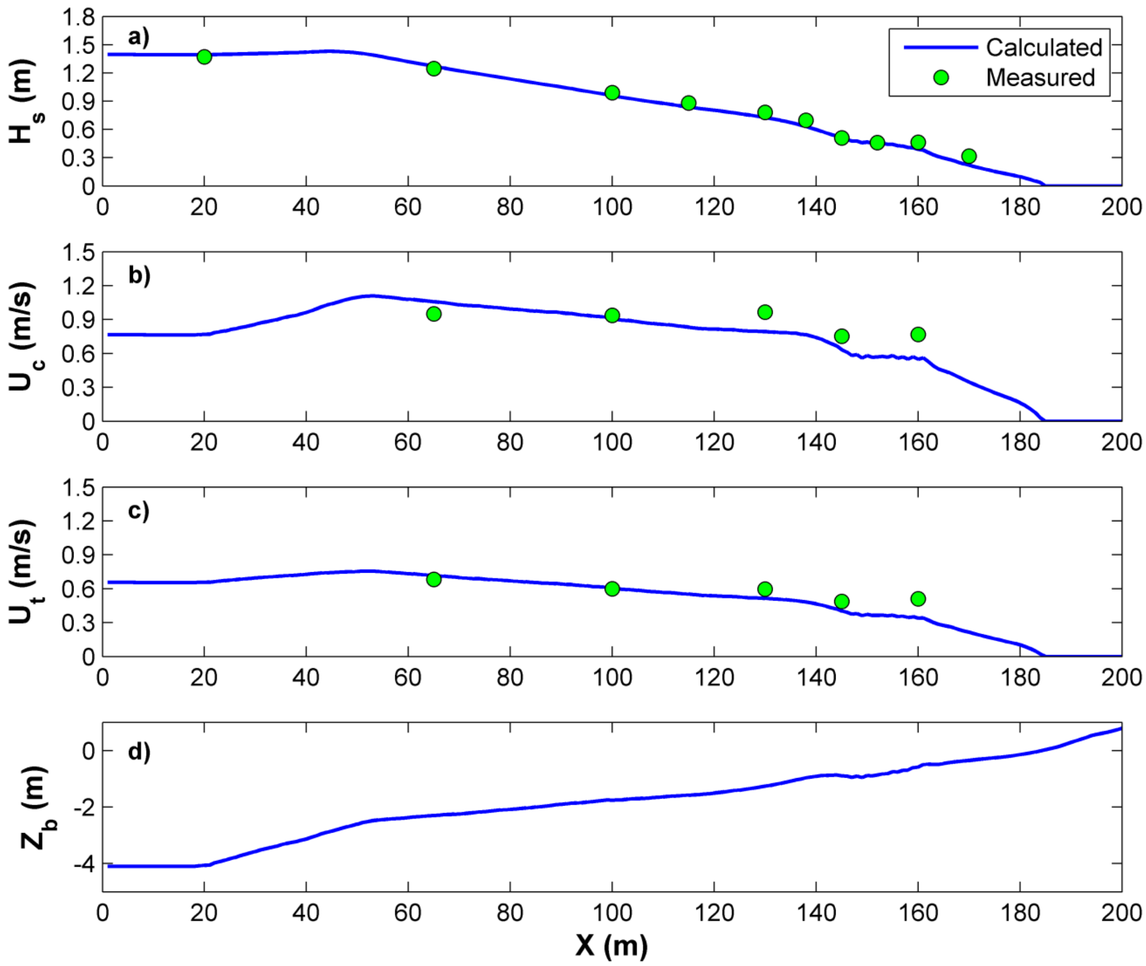

Fig. 5. Comparisons between calculated significant wave height (a), peak onshore (b) and offshore (c) orbital velocities with measurements for Test 1B (Roelvink and Reniers, 1995) together with profile shape.

3.3 Field data at Egmond beach, The Netherlands

A data set consisting of significant wave height and near bed peak orbital velocity collected during a field campaign on Egmond beach, the Netherlands, during 6 weeks from October to November, 1998, were employed to validate the model. The beach topography was characterized by two parallel sand bars (Ruessink et al., 2000; 2001; Kleinhout, 2000). The offshore wave conditions were measured with a wave buoy in a water depth of 16 m, approximately 5 km offshore, and a wide range of wave conditions were observed. The maximum offshore incoming significant wave height reached 5.5 m during the storm. The significant wave period ranged from 3 s to 10 s, and the incident wave angles between -45^0 and +45^0 relative to shore normal. The tidal range varied from 1.4 m to 2.1 m. The significant wave height was measured at six locations from E1 to E6 (Fig. 6), whereas the peak near bed onshore and offshore velocities were measured at five locations E1, E2, E3, E4, and E6.

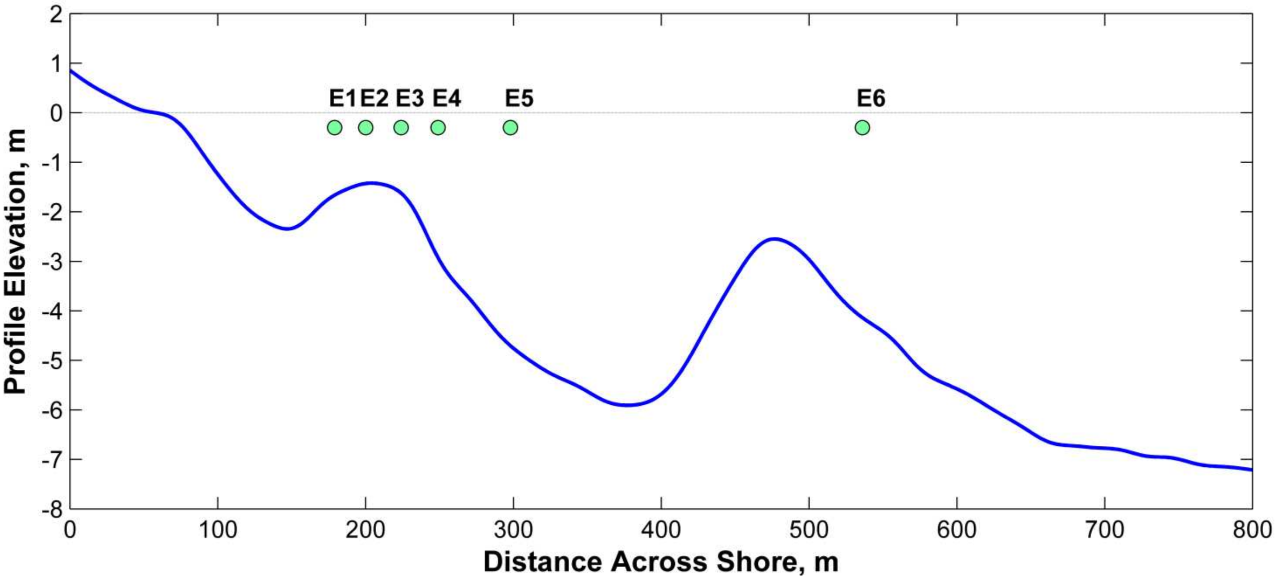

Fig. 6. Profile shape measurement locations at Egmond Beach, the Netherlands.

The validation of the significant wave height was presented in detail in Nam et al. (2017). The simulated significant wave height agreed well with the measurements at all six locations. For all data points at the 6 locations (E1-E6), the relative rms error was 10.3 %, the relative bias 0.019, and the coefficient of determination R^2 about 0.95.

The near-bed peak onshore and offshore orbital velocities were calculated and compared with measurements at the five locations. The comparisons between calculated and measured peak onshore and offshore velocities are illustrated in Fig. 7a and Fig 7b, respectively. The calculations of the peak onshore orbital velocity produced slight overestimations at the four locations in the vicinity of the inner bar (E1 to E4). However, at position E6 near the outer bar, where the peak onshore velocity observed was more than 2 m/s, the calculations are significantly smaller than the measurements. The relative rms error for the peak onshore velocity is about 21.3%, and the relative bias is quite small, approximately 0.013. The scatter index is 0.23, and both the coefficient R^2 and the Brier skill score are equal to 0.68.

The predicted peak offshore velocity somewhat underestimated the measurements. Therefore, the relative bias obtained is negative, approximately -0.068. As for the peak onshore velocity, the largest discrepancies between calculations and measurements for the peak offshore velocity were obtained at location E6. At other measurement locations, the prediction of the peak offshore velocity was in good agreement with the measurements. The relative rms error is approximately 21.2 % and the scatter index about 0.225. Both the coefficient of determination and Brier skill score are 0.64, a bit smaller than for the peak onshore velocity, but still indicating a good performance for the model.

4 Conclusions

A numerical model for determining the nonlinear near bed orbital velocity in the shallow water was presented. The method introduced by Isobe and Horikawa (1982) was modified, in which the correction coefficient and maximum skewness were dependent on the Ursell number. The model was validated against different data sets from small-scale wave flume experiments at Delft University of Technology, large scale wave flume experiments at Delft Hydraulics, and field campaigns at the Egmond beach in the Netherlands. The validations showed that the predictions of significant wave height, peak onshore and offshore velocities were in very good agreement with measurements. The rms error for significant wave height varied from 5.2 % - 10.3 %. For the peak onshore velocity, the calculations in the surf zone slightly underestimated the measurements in Test B2 and Test 1B, whereas they underestimated the measurements to a larger degree at the location near the outer bar at Egmond beach. The rms errors for peak onshore velocity were from 8.7 % - 21.3 %. The calculation of peak offshore velocity somewhat underestimated measurements for all employed data sets, and the rms errors varied between 15.6% and 21.2 %. Overall, the model successfully predicted the nonlinear near bed orbital velocity in the nearshore, especially in the surf zone and shallow water.

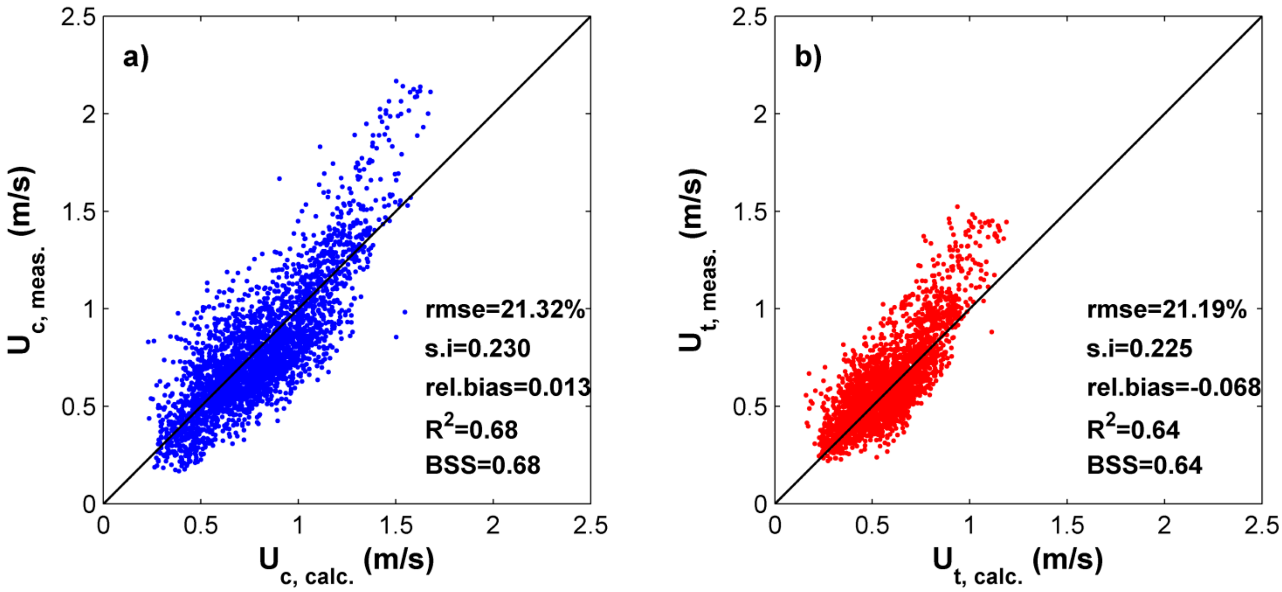

Fig. 7. Comparisons between calculated peak onshore (a) and offshore (b) orbital velocities with measurements collected at Egmond beach, the Netherlands.

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