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Numerical Simulation and Large-Scale Physical Modelling of Coastal Sand Dune Erosion

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ABSTRACT

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Coastal sand dune system is important in the nearshore environment for sand supply, ecosystem, and hazard mitigation. In this study, a process-based morphological model was performed and the results were compared with large-scale laboratory experimental data. Two-dimensional large-scale laboratory experiments were conducted with 1:6 geometric scale in the large wave flume (104m (L) x 3.7 m (W) x 4.6 m (D)) of the Hinsdale Wave Research Laboratory at Oregon State University (Maddux et al, 2006). Several different wave conditions were used with different water levels in this experiment including pre-storm, storm, and post storm based on random wave time series by using TMA spectrum. The data set included cross-shore Wave heights, fluid velocities, and the profile changes of the beach and dune. The process based model, XBeach (Roelvink et al., 2009) was used to simulate the nearshore hydrodynamics and bed level change during storm wave condition. Several semi-empirical parameters were used in the XBeach model to predict morphodynamic process (Roelvink et al., 2009) and recently the updated parameters (*WTI* settings) were suggested based on the results of field observations. The present study ran the XBeach model by using both *default* and *WTI* settings and compared with the results from the experiments. The results showed that the model results with *WTI* settings showed good agreement with the measured beach profile while the model results with *default* settings over-predicted the offshore sediment transport and dune erosion. Especially, the wave skewness (*facSk*) and asymmetry (*facAs*) gave the highest contribution to predict dune erosion.

ADDITIONAL INDEX WORDS: *Dune erosion, sediment transport, XBeach model, large-scale experiment,*

INTRODUCTION

Beach erosion is a chronic problem for many coastal communities. Especially, coastal sand dune is essential in the nearshore environment for sand supply, ecosystem, and ability to reduce storm damage on coastal properties. Recent events such as Hurricanes Katrina and Sandy destroyed the coastal sand dune, which can result in the serious damage to the environmental and economy of coastal community (Benimoff et al., 2015; Vigdor, 2008). Therefore, accurate prediction of the sediment transport and erosion of coastal sand dune is necessary to protect coastal community and to guide management or restoration efforts. Even though various researches carried out on the sediment transport and bed level change of coastal sand dune, the ability to accurately predict morphodynamics has not been significantly improved (Roelvink et al., 2009; McCall et al., 2010; Kobayash and Jung, 2012; Do et al, 2014). The major reason is that a governing equation cannot be available to describe the motion of large number of sediment particles. For this reason, the empirical sediment transport models have been developed based on the reliable experiment and field data. Unfortunately, coastal morphology is highly complex because the movement of sediment particles is determined by their prosperities (diameter, specific gravity, roughness and porosity etc..), as well as wave breaking and wave-induced current. So, understanding of the coastal sand dune erosion process during storm event is insufficient, and it is still difficult to predict the dune erosion by numerical modelling.

Over the years, cross-shore numerical models such as SBeach (Larson and Kraus, 1989) and CSHORE (Kobayashi et al., 2010) have been developed and predict the storm-induced beach and dune erosion profile. However, these numerical models do not account for the generation of low frequency wave motion during storm event, which is important process to predict the erosion of coastal sand dunes. To predict the morphodynamics on the coastal sand dune accurately, this study was carried out the numerical simulation using the process based numerical model, XBeach (Roelvink et al., 2009). This model was widely used as a modelling tool for beach and dune erosion, such as Sateague Island in Maryland (Roelvink et al., 2009), Santa Rosa Island in Florida (McCall et al., 2010) and Ostend Beach in Belgium (Bolle et al.,2010). Recently, its used have been applied to the modelling of post-storm beach accretion and recovery (Pender and Karunarthna, 2013) and gravel beach variability (McCall et al.,

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2015). Although XBeach has been extensively examined and validate for beach erosion and accretion, it cannot be predicted post-strom coastal sand dune erosion accurately.

The main objective of this study is to apply and validate the XBeach model based on the two-dimensional large-scale laboratory test resuls, which were conducted in the large wave flume of the Hinsdale Wave Research Laboratory at Oregon State University (Maddux et al, 2006). A number of hydrodynamical and morphodynamical parameters are used in the XBeach model to predict beach and dune erosion (Roelvink et al., 2009). Recently, these parameters (WTI settings) were updated to guide the protection of coastal sand dune in the Netherlands (van Geer et al., 2015). The present study ran the XBeach model by using both default and WTI settings and compared with the beach profile data from the experiments. The compared XBeach is used to estimate the sediment volume change in the nearshore area and interpret the sediment transport and bed level change of coastal sand dune.

PHYSICAL MODELING

Two-dimensional large-scale wave flume tests have been conducted with 1:6 geometric scaled model of the sand dune in the large wave flume (104m (L) x 3.7 m (W) x 4.6 m (D)) of the Hinsdale Wave Research Laboratory at Oregon State University by Maddux et al (2006). 800m^3 of natural beach sands from the Oregon coast were used to build the beach profile with the sand dune in the wave flume. The median diameter of the beach sands was 0.2mm. The initial profile of the beach and dune was selected by considering the field observation results of the various east coast and Gulf coast dune systems in the United States as shown in Figure 1.

Eight resistance type wave gages were deployed on the side wall of the flume and three ultrasonic wave gages (range finder) were used to measure the water surface elevations in both deeper and shallower depth regions. Three ADVs (Acoustic Doppler Velocimeter) were installed at the same cross-shore locations as the ultrasonic wave gages to measure the water surface elevation and velocities simultaneously (the wave velocity data are not shown in this study).

Several different wave conditions were used with different water levels including pre-storm, storm, and post-storm based on random wave time series by using TMA spectrum (r = 3.3). Initial beach profile reached the equilibrium state under the pre-storm wave conditions. As shown in Table 1, input wave and water level conditions started smaller waves and lower water levels, covered storm wave conditions with surge levels, and finally reached the post-storm conditions. Table 1 shows the wave and water level conditions in the experiments. 15-minute burst of waves were run, and profile survey was performed by MTA (multiple transducer array) after every run.

Table 1. *Input wave and water level conditions at the most offshore wave gage. Hs, Tp, and WL denote significant wave height, peak period and water level respectively.*

Case	Hs (m)	Tp (s)	WL (m)
Initial	0.25	4.90	3.96
SC1	0.50	2.04	4.00
SC2	0.67	3.06	4.05
SC3	1.00	4.80	4.09
SC4	1.17	4.90	4.13
SC5	1.00	4.90	4.09
SC6	0.67	4.90	4.05
SC7	0.50	4.90	4.00
Recovery	0.25	4.90	3.96

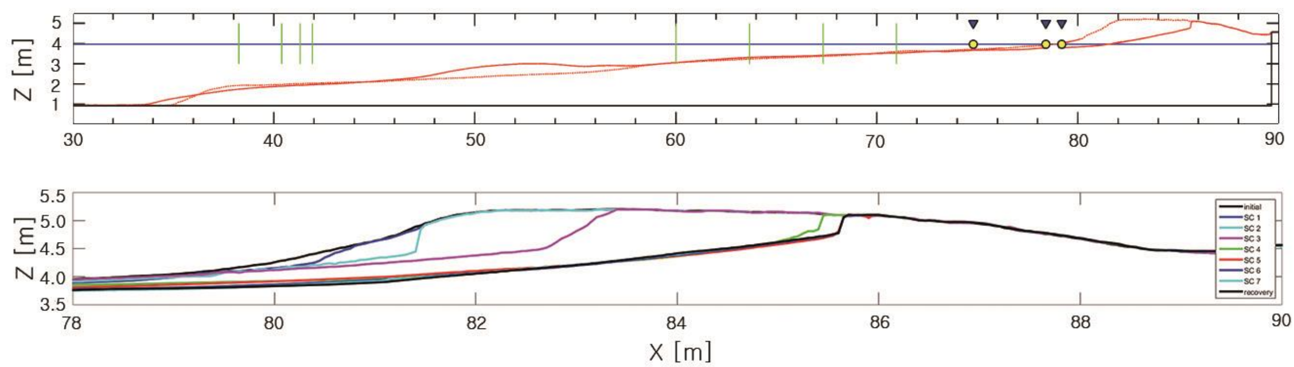

Figure 1. Cross-sectional view of the beach and dune profiles in the wave flume. Red lines are initial and final profiles. Green lines denote resistance wave gage locations and blue triangles show the locations of ultrasonic wave gages. (Maddux et al., 2006)

NUMERICAL MODELING

In this study, the process based model, XBeach (Roelvink et al., 2009) was used to simulate the nearshore hydrodynamics and morphodynamic process under each experimental condition. XBeach is an open-source, process-based (i.e. based on the physical principles) numerical model which have modules for predicting wave propagation, sediment transport and bed level change in the nearshore area, including swash zone. In this study, XBeach (version Groundhog Day) was set-up in hydrostatic (instationary) surf beat mode to consider the generation of low frequency motion important for erosion of beach and sand dunes (Roelvink et al., 2009; Reniers et al. 2006). The hydrostatic mode is specified to calculate a short-wave conversion separately from the long-wave motion that is simultaneously resolved in the non-hydrostatic mode. That is, the current, wave run-up and suspended sediment transport caused by long wave motion are resolved in the non-hydrostatic mode based on the nonlinear shallow water equation, while short-wave motions are solved by time-dependent, wave action balance equations.

This study constructed a variable resolution grid as shown in Figure. 2 to satisfy the CFL (Courant–Friedrichs–Lewy) criterion for the best model performance. The criterion is based on the low-frequency wave-induced current to solve non-linear shallows water equations. This study generates 126 grid points and the resolution is 0.15 m near the coastal sand dune, toward the seaward boundary increased to 2.0 m. Water depth was generated using pre- and post- beach profile data measured from wet (MTA, Multiple Tranducer Array) and dry (laser) surveys. The beach sand is characterized by the median diameter of 0.2 mm where the bottom sediment porosity is assumed as 0.4. The specific gravity of sand was also determined as 2.65.

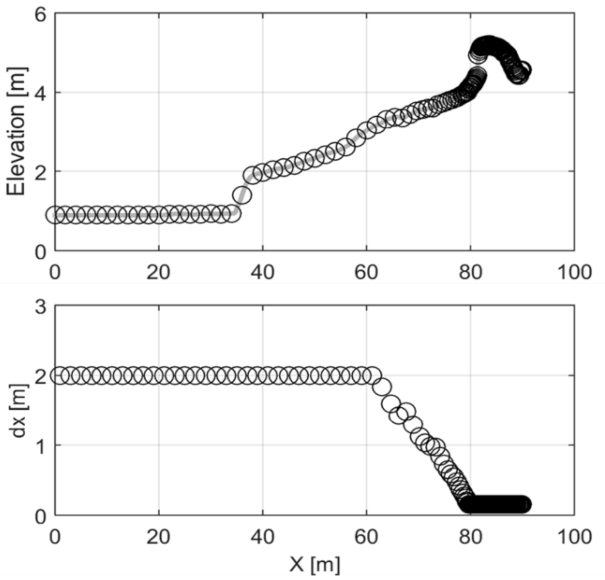

Figure 2. Spatial variation grid (top) and resolutions (bottom) in the XBeach modelling.

In this study, sediment transport and dune erosion were reproduced under seven experiment scenarios. The input to XBeach model includes the water level S, and the incident wave conditions represents by H_{mo} and T_p at the offshore boundary in water depth of approximately 3 m. The wave boundary was then forced at the offshore boundary using time-varying Joswap spectrum to derive from a spectral significant wave height and peak wave period with peak a peak enhanced factor, $\gamma = 3.3$. This approach is capable to reproduce the nearshore hydrodynamics and morphodynamics on the time scale of wave-groups, including surfbeat (long waves, infragravity waves). It is well known that the long wave is important to predict the dune and berm erosion above MST on the time scale of storm events.

A number of semi-empirical parameters are used in the XBeach model to predict sediment transport and bed level change in the nearshore area (Roelvink et al., 2009; McCall et al., 2010). XBeach developers have already defined the *default* settings for these parameters manual. These parameters will be re-determined by the WTI 2017 (Wettelijk Toets Instrumentarium) project and will use the protection of coastal sand dune in the Netherlands (van Geer et al., 2015). The *WTI* calibration parameter were determined using a large database of laboratory and field measurements under high wave conditions. Table 2 are listed in the optimization value of 9 input parameters,, which mostly related to flow and wave breaking process, but also to sediment transport and bed level change in the nearshore area: *fw* is the bed friction factor; *cf* is the friction coefficient in flow; *gamma* is the breaker parameter; *gammax* is the maximum ratio wave height to water depth; *beta* is the breaker slope coefficient in the roller model; *alpha* is the wave dissipation coefficient; *wetslp* is a critical avalanching underwater slope; *facAs* and *facSk* are calibration factors in time averaged flows, due to wave asymmetry and skewness, respectively; In particular, it is known that the *facSk* and *facAs* contribute the sediment transport and morphological change of coastal sand dune (Roelvink et al., 2009; Dissanyake et al., 2015). In this study, numerical simulation was carried out using *WTI* and *default* setting.

Table 2. *XBeach WTI parameters compared to Default Parameters (van Geer et al., 2015).*

Parameter	*Default* Settings	*WTI* Setting
fw	0.000	0.000
Cf	0.003	0.001
gamma	0.550	0.541
gammax	2.000	2.364
beta	0.100	0.138
alpha	1.000	1.262
wetslp	0.300	0.260
facSk	0.100	0.375
facAs	0.100	0.123

RESULTS

In this study, the numerical model is compared with the beach profile data obtained through large scale physical modelling of dune erosion. The input parameters are taken as the same as the *default* settings and *WTI* settings in Table 2. Figure.3 presents the input pre-storm profile, and the measured and computed final profiles for period SC3, SC4 and SC 5, using *default* and *WTI* settings. The use of *default* setting over-predict the offshore sediment transport, so the predicted coastal sand dune was almost destroyed during SC4 period. However, the simulated erosion and deposition patterns in the *WTI* setting seems to be in good agreement with experiment data, except for the front of coast sand dune and berm area. This result to shows that the wave skewness (*facSK*) and assymetry (*facAS*) are closely related to nonlinearity of wave, so it is proportional to the onshore bed load sediment transport and offshore suspended sediment transport. The sediment transport and bed level change of the dune front and low swash zone, causing that episodically sand is released from the dune by avalanching is complex and difficult to accounted in the numerical simulation. In the XBeach model, the avalanching of dune face is used as a simple avalanching algorithm in which the dune faces collapses if a critical avalanching slope (*dryslp*) is exceed. So, the erosion of dune face is not easy to predict accurately.

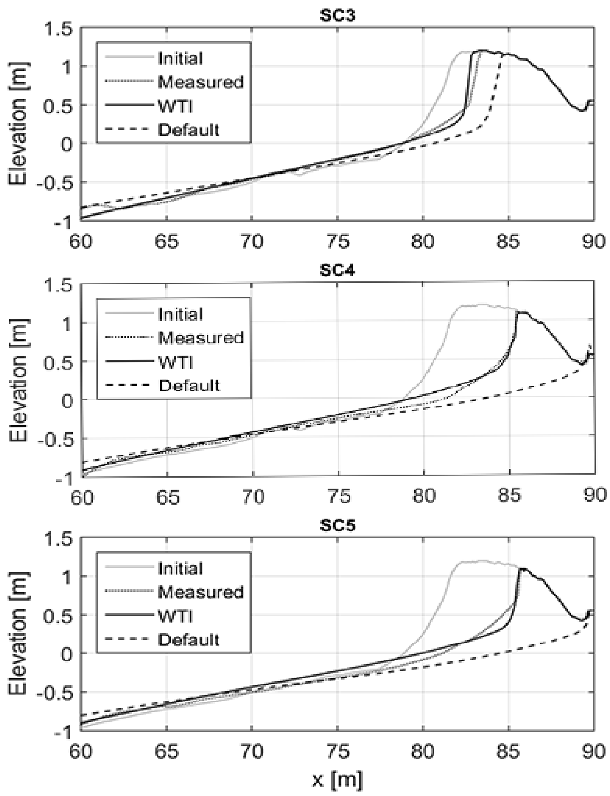

Figure 3. Measured and computed final profiles starting from initial profile for SC3 (top), SC4 (middle) and SC5 (bottom).

Figure 4 shows the measured and computed erosion (positive) or accretion (negative) volumes above mean sea level (MSL hereafter, top panel) with *WTI* and *default* settings. The computed erosion volume above MSL was 4.78 m^3/m for *WTI* setting and 7.88 m^3/m for *default* settings, both higher than the measured value (4.31 m^3/m). For *WTI* setting, the erosion volumes are predicted well, but in case of *default* setting over-predicted the offshore sediment transport and dune erosion. To estimate the model performance including the surf zone (wave-breaking zone), measured and computed erosion volume below the MSL and above -2 m are shown in Figure 4 (bottom). This figure also shows that the simulation results with *WTI* setting reproduced the accretion while the results with default setting over-predicted. Moreover, both two figures indicate that the most of cross-shore sediment transport in this experiment was occurred above the the water depth with 2m because the erosion volume above the MSL is balanced with the accretion volume between the MSL and the water depth of 2m.

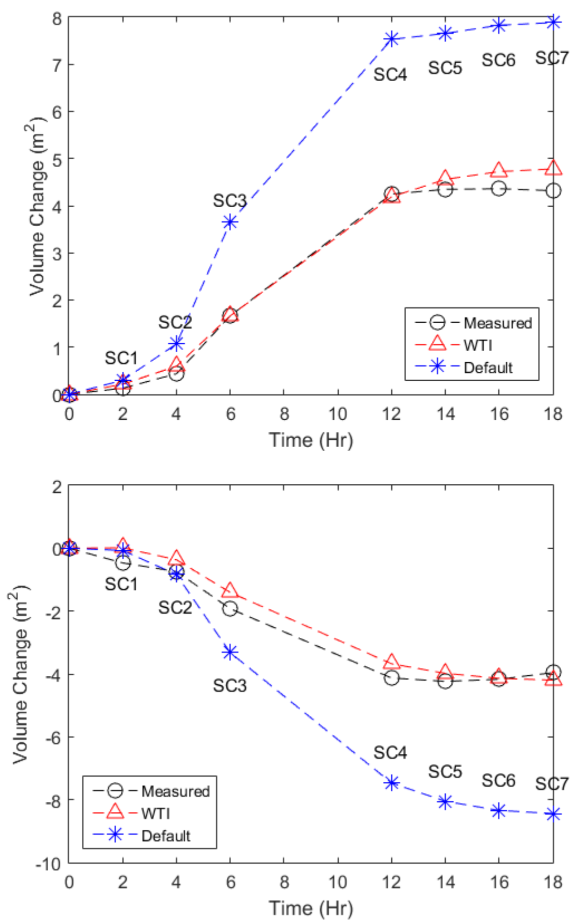

Figure 4. Measured and computed erosion volumes for *WTI* and *default* setting (top: above the MSL; bottom: below the MSL and above -2m).

CONCLUSIONS

The large-scale movable bed experimental data set was adopted in this study to investigate the beach and dune profile changes and volume changes. The data include the cross-shore variation of the water surface elevation and the beach and dune profile changes under pre-storm, storm, and post-storm conditions.

In the present study, a process based morphological modeling by using XBeach was performed to predict the profile changes of sandy beach and dune. Recently modified parameters, WTI parameter, were used to simulate the dune erosion. The simulation results were compared with large-scale laboratory experimental data for the model verification.

Based on the numerical modeling and the analysis of the experimental data, the following conclusion can be drawn:

- The profile survey results in the experiments show that the major dune erosion occurred in SC3 and SC4. Therefore, dune erosion can be affected by both wave condition and water level rise.
- In the XBeach modeling, the simulation results with default parametric settings poorly predicted the dune erosion so that most of the dune section were eroded by SC4. On the contrary, the modeling results for dune profile changes based on the WTI parameters show a good agreement with the experimental results.
- The XBeach model with WTI setting precisely predicted the erosion volume changes above the mean sea level (MSL) and the accretion volume variations between the MSL and the water depth of 2m, compared with the experimental results, while the model with default parameters overpredicted those values. Therefore, WTI parameters are more promising to predict both dune erosion and offshore sediment transport in the erosive condition.
- Overall, the cross-shore sediment transport budget is balanced from the dune area to the water depth of 2m.

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