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A case study on dune response to infragravity waves

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Abstract A series of numerical simulations were conducted using the process-based model XBeach to investigate dune response under normal and getting rid of infragravity wave conditions with different slopes. Erosion volume upside the dune toe and dune top recession are set as indicators for dune vulnerability as well as defence capacity for its front-beach. Results show that both dune erosion volume and dune top recession decrease with gentler dune slopes. Of all the simulation cases, dune with a face slope of 1/1 lost most sand and supplied most sand for lower-bed. The presence of infragravity waves is validated to be crucial to dune vulnerability. The dune erosion volume is shown to decrease by 44.5%~61.5% and the dune top recession decreased by 0%~45.5% correspondingly, in the case that infragravity motion is not taken into account during simulation for different dune slopes.

1. Introduction

Coastal area provides resources such as biodiversity, fishing and travelling. At the same time, most of the natural sandy beaches are threatened by erosion each year. Barrier dune consists 10% of the global coastline, which faces the risk for erosion and flooding [1]. Hays and Boothroyd attributed short-term beach dune erosion to storm surge influence. Coastal dunes, in another mean, is a natural hazard defence for inland area, especially during storm conditions. There has been research focusing on the dynamic sediment adjustment within the beach-dune system [2]. Dune erosion during storm surges is divided into four regimes including swash, collision, overwash and inundation by Sallenger [3] to describe the corresponding wave effects on sediment transport and dune vulnerability. Research on beach and dune vulnerability during variable wave conditions is significant for coastal planning and management. And there has been plenty of studies using approaches include field investigation [4][5], laboratory experiment [6][7] and so forth.

Existing analytical and empirical means describe beach evolution in distinguished time scales from several years to a few days. The Bruun rule [8][9], named by Schwartz [10], is a widely used model for predicting long-term sand beach erosion due to sea level rise. Dean [11] developed the equilibrium profile concept to describe beach profile evolution. Besides, the 1D semi-empirical SBeach model [12] was based on sediment equilibrium theory, which is also a practical tool to investigate beach erosion. Edelman [13] was the first one to propose dune erosion prediction method, which was latter modified by Van de Graaff. But it was still rough due to lack of field measured data. Most of the models above are either insufficient or inaccurate to describe beach and dune erosion during intensive storms in a short time scale. On the other hand, process-based models usually take more physical mechanisms into account than the above analytical and empirical ones. XBeach is a newly developed 2D numerical model employing structured grid to simulate hydrodynamic and morphodynamic processes and



impacts on sandy coasts [14]. It is actually one of the most advanced numerical model in assessing coastal risk during extreme conditions so far.

2. Method

2.1. Simulation scheme

There have been researches investigating vulnerability indicators for coastal dunes to predict their vulnerability during storm surges [15]. When storms attack sandy beaches with maximum wave run-up not exceeding dune top, swash and collision regime occur. The majority of sediment collapses from dune face and partially deposits on the dune toe, while another part is transported offshore by undertow and finally deposit on the front-beach. During mild wave conditions, the eroded sediment returns back to the dune again by the asymmetric and skew orbit wave motions. Thus the erosion volume upside the dune toe can in fact be set as a defence capacity indicator for the dune-developed sandy beach. Besides, the dune top recession is also crucial for dune stability. Quantificationally, dune with different slopes have multiple defence capacity. On the other hand, infragravity waves, especially during extreme wave conditions, was proved to be crucial to nearshore regions [16]. Thus, dune erosion volume and top recession are investigated in our study, and their difference in case that infragravity waves are not evolved during simulation are considered. The delft flume test 1993 conducted several groups of dune erosion experiments under distinguished initial conditions. And our numerical test cases are set based on the Delft flume test 1993 2E and its original validation with Xbeach by Deltares in 2004 [17], with an excellent BSS skill [18] of 0.84. Only the initial profiles are modified in our study into profiles with dunes whose slopes vary from 1/1 to 1/10. The default incident wave boundary condition is adopted in all conditions. And the default model settings are employed except the infragravity term, with one half of cases the infragravity waves are present and the other half not. The simulation cases are listed in table 1.

Table 1 Simulation cases

Case	Defence form (dune face slope)	Model settings for the infragravity term
1	Dune 1/1	lwave=0/1
2	Dune 1/2	lwave=0/1
3	Dune 1/3	lwave=0/1
4	Dune 1/4	lwave=0/1
5	Dune 1/5	lwave=0/1
6	Dune 1/6	lwave=0/1
7	Dune 1/7	lwave=0/1
8	Dune 1/8	lwave=0/1
9	Dune 1/9	lwave=0/1
10	Dune 1/10	lwave=0/1

2.2. Model employed

The 1D structured XBeach model was employed in our study. The model consists of wave, current as well as sediment transport sub-models, in which depth-averaged nonlinear Generalized-Lagrange-Mean shallow water equation is employed to simulate wave generated current and low frequency motions. The GLM nonlinear shallow water equations are listed as follows:

$$\frac{\partial u^L}{\partial t} + u^L \frac{\partial u^L}{\partial x} + v^L \frac{\partial u^L}{\partial y} - f v^L - v_h \left(\frac{\partial^2 u^L}{\partial x^2} + \frac{\partial^2 u^L}{\partial y^2} \right) = \frac{\tau_{sx}}{\rho h} - \frac{\tau_{bx}^E}{\rho h} - g \frac{\partial \eta}{\partial x} + \frac{F_x}{\rho h} \quad (1)$$

$$\frac{\partial v^L}{\partial t} + u^L \frac{\partial v^L}{\partial x} + v^L \frac{\partial v^L}{\partial y} - f u^L - v_h \left(\frac{\partial^2 v^L}{\partial x^2} + \frac{\partial^2 v^L}{\partial y^2} \right) = \frac{\tau_{sy}}{\rho h} - \frac{\tau_{by}^E}{\rho h} - g \frac{\partial \eta}{\partial y} + \frac{F_y}{\rho h} \quad (2)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial hu^L}{\partial x} + \frac{\partial hv^L}{\partial y} = 0 \quad (3)$$

In which τ_{bx} and τ_{by} are the bed shear stress; η is the water level; F_x and F_y are the wave induced stresses; ν_h is the horizontal viscosity and f is the Coriolis coefficient. The generalized Lagrange velocity consists of Euler velocity and Stokes drift.

The Soulsby-van Rijn's sediment transport model is employed to calculate equilibrium sediment concentration. Sediment concentration in the model is governed by the depth-averaged advection-diffusion equation as follow:

$$\frac{\partial hC}{\partial t} + \frac{\partial hCu^E}{\partial x} + \frac{\partial hCv^E}{\partial y} + \frac{\partial}{\partial x} \left[D_h h \frac{\partial C}{\partial x} \right] + \frac{\partial}{\partial y} \left[D_h h \frac{\partial C}{\partial y} \right] = \frac{hC_{eq} - hC}{T_s} \quad (4)$$

Where C represents the depth-averaged sediment concentration which varies on the wave group scale and D_h is the sediment diffusion coefficient. The entrainment of the sediment is represented by an adaptation time T_s .

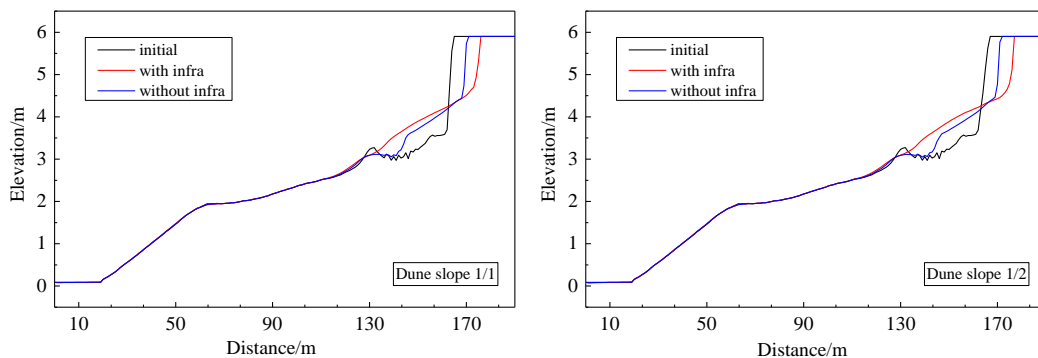
The wave balance equation takes wave refraction, shallow water deformation, current-wave interaction and energy dissipation due to wave group break into account, which is shown below:

$$\frac{\partial A}{\partial t} + \frac{\partial c_x A}{\partial x} + \frac{\partial c_y A}{\partial y} + \frac{\partial c_\theta A}{\partial \theta} = -\frac{D_w}{\sigma} \quad (5)$$

In which A is the wave action, and D_w represents dissipation led by wave breaking, bottom friction and vegetation. Wave-current interaction is considered by correcting the wave number and flow velocity in the equation above. The surface roller effect is also introduced to complement the short wave action balance.

3. Result

The simulated profile variations are listed below in figure 1. Each figure, with specific dune slope marked on the lower right corner individually, contains initial profile and final profile under default wave boundary condition as well as condition without infragravity waves during the simulation procedure.



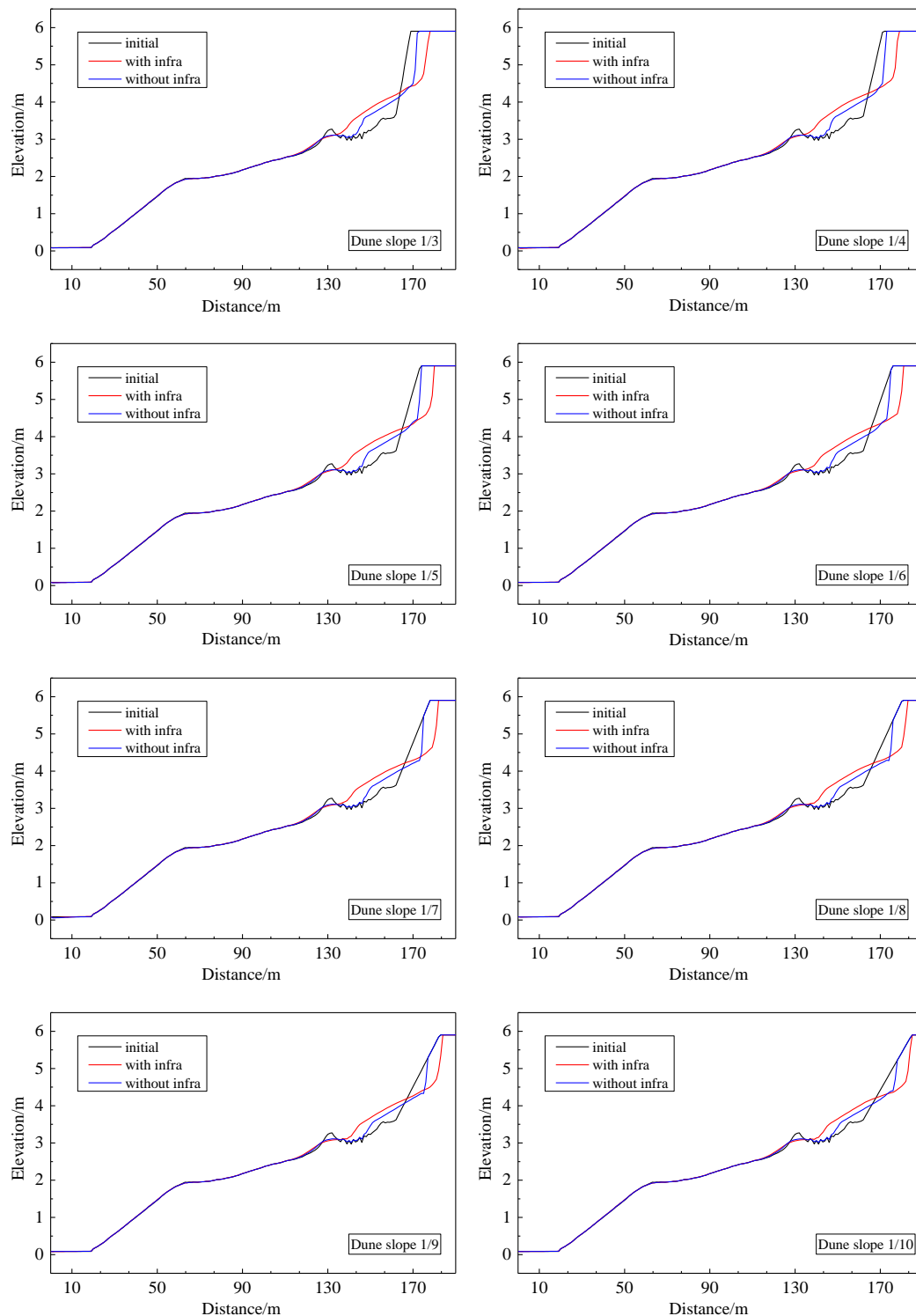


Figure 1. Profiles with different slopes shaped under varied wave conditions

The erosion volume and dune top recession of all sand dunes under default incident boundary condition and case the infragravity waves are not take into account are shown in figure 2 and figure 3 respectively.

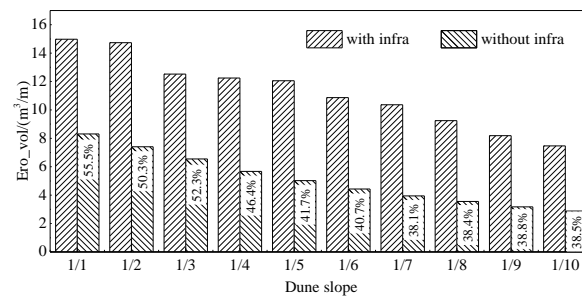


Figure 2. Erosion volume upside the toe of dune for all cases

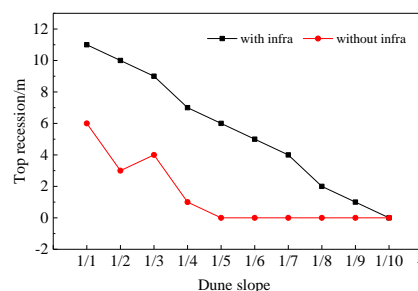


Figure 3. Dune top recession for all cases

Results show that dune eroded mainly in oscillation regime during simulation. The maximum wave run-up hardly exceeded dune top for all cases. Sand collapsed from the upper side of dune face and deposited lower in the bed or transported opposite of the incident direction by undertow in intensive wave conditions.

Among all of the test cases, the existence of infragravity waves results in more erosion from the dune face. It can be inferred that the erosion volume for dunes with slopes ranging from 1/1~1/10 decreased significantly to 38.5%~55.5%, and the dune top recession decreased by 45.5%~0% correspondingly when taking the infragravity motion in consideration in the model. All cases demonstrated that dune erosion volume and dune top recession increase with higher dune face slope, which, in another way, increase sediment supply for beach in front of the dune although more erosion and recession means higher dune vulnerability. The dune top recession forms nearly linear relation with dune slope under default boundary condition, taking infragravity waves into account. Of all the simulation cases, dune with a face slope of 1/1 lost most sand and supplied most sand for front-beach in turn. In the cases that infragravity motion is get rid of the simulation, the dune top recession for dunes with slopes between 1/5 and 1/10 is zero, which is the case only when dune slope equals 1/10 for default cases.

4. Discussion and conclusion

Dune vulnerability is fatal for sandy beaches, especially during storm conditions. Specifically, physical dimension and sediment composition are critical stability parameters for dunes. Erosion volume upside the dune toe and dune top recession are set as indicators to evaluate dune erosion strength as well as protection capacity to its front beach in our study. It is inferred that these two indicators vary with different dune slopes. Besides, the infragravity waves play an important role in the nearshore dune erosion, which is also confirmed in our study. During transmission, most of the incident short wave breaks in shallow water and the energy is passed to motions with lower frequency. Low frequency waves are less affected by the shallow water region because of their relatively smaller amplitude and longer wavelength than short wave. The low frequency motions therefore dominate the wave energy spectrum near the shoreline in shallow water. After hitting the dune face, some parts of long waves reflect and another part become leaky waves. Van Dongeren et al [19] showed that the slope of the nearshore also affects the growth of the low frequency wave and controls how much of the

incident wave is reflected. So enough attention should be paid to nearshore low frequency motions in further study and engineering practice.

Due to lack of field survey data, the Deltares's laboratory data is used in our study. It should be mentioned that, however, field and laboratory scenes are quite different because realistic sandy beach & dune erosion is complex and usually affected combinedly by many factors such as longshore transport gradient, human influence, the prevailing incident wave direction and so forth. And the laboratory-data-based simulation in this paper is able to describe quantificationally some major factors including incident wave component, dune slope and erosion volume in specific dune erosion circumstance.

The current used XBeach model is still under development to improve its capabilities, and the low frequency wave might be overestimated to a certain extent in the nearshore region. But it is still quantificationally shown from this study that the presence of infragravity waves lead much more dune erosion in all simulation cases. And further study is needed to investigate the mechanism between short and long wave interaction in the nearshore to better model sandy beach & dune erosion process.

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