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A 3D Physical Model Study of Reinforced Dune Evolution During Storm Conditions

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Abstract: A three-dimensional physical model study was conducted in a wave basin for a reinforced dune consisting of a rubble mound hard structure covered by a layer of sand. The setup consisted of a beach with two seaward slope configurations. Shore-normal and oblique wave forcing with a JONSWAP spectral shape was utilized to generate model conditions producing severe erosion of the sediment layer as well as overtopping and overwash. A comparison between the cross-shore profiles of the modeled beach showed that storm surge progression strongly affected the erosion process and the associated coastal profile evolution. Eroded sediment moved offshore creating a submerged bar during the collision regime even before the onset of overtopping. This increased wave energy dissipation via wave breaking. The surge level was found to be the main factor contributing to reinforced dune profile evolution during storm conditions compared to secondary factors including seaward dune slope and wave directionality. The data collected from this study is being used to assess the viability of such hybrid coastal structures for storm surge suppression and to improve numerical modeling capabilities.

Keywords: wave basin, hybrid structure, storm surge, morphology, dune erosion, wave reflection

1 Introduction

Coastal landscapes worldwide are experiencing intensifying pressure as a consequence of rapid population growth and increasing demand for infrastructure development to sustain commercial, residential and tourist activities. Global climate change resulting in accelerated sea level rise adds to the pressure on coastal ecosystems leading to exacerbating erosion and accelerating shoreline retreat (Nordstrom, 2000; Slott et al., 2006). Sea levels are expected to continue to rise in the future at a faster rate: global sea level rise (SLR) projections range from 0.2 to 2.0 m by 2100 (IPCC 2014; Parris et al., 2012) with some regions experiencing higher SLR due to localized processes. Coastal storms are also predicted to become more intense and perhaps more frequent (Webster et al., 2005; FitzGerald et al., 2008), increasing their destructive force by up to 25 % to further increases the vulnerability of coastal communities (Scavia et al., 2002).

Shorelines with sandy beach and dune systems are natural coastal protective buffers for coastal communities against extreme events. However, dune resistance to extreme events could fail by frequent erosional cycles due to storm impact as a result of storm-driven surges, wind and waves. Such events can result in large morphological changes, damage to infrastructure and loss of lives. Historically, these effects have been mitigated using ‘hard’ coastal structures aimed at strengthening the coastline locally, such as seawalls, breakwaters, and wooden or rubble mound groins (Nordstorm, 2000; Rippon, 2000; Charlier et al., 2005; Griggs, 2005a; 2005b). While the use of hard engineering approaches can be important and highly effective, these solutions can also be costly to build and maintain (Anthony and Gratiot, 2012; Bosello et al., 2012). In some situations, existing large hard structures can experience overtopping by waves and catastrophic failure in light of predicted sea level rise and storm intensity with risks not only to infrastructure but also to human safety. In addition, there is always the need to monitor, repair, and maintain such structures, which is costly. Thus, a growing research interest exists to enhance coastal resilience by re-enforcing dunes with hard structures or using a combination of natural ecosystems and built infrastructure, or ‘hybrid systems’. These systems can capitalize on the strength of ‘hard’ and ‘soft’ approaches while minimizing the weaknesses of each, especially in areas with limited space for coastal protection measures and a desire for natural-looking aesthetic appearance.

1.1 Literature Review

Dune or beach morphology changes in the presence of a hard structure have been studied by Van Gent et al. (2008), Boers et al. (2011), Van Thiel (2012) and Figlus et al. (2015), among others. Van Gent et al. (2008) completed a large-scale physical model experiment to explore the effects of a collapsed dune revetment on dune erosion and compared it to the situation of a dune without a revetment. One configuration was a sloping dune revetment, and the other was a horizontal and a vertical revetment with a sandy beach. It was observed that the volume of dune erosion in the case of the collapsed dune revetment was similar to that of dune erosion without revetment. Also, the dune revetment structure provided protection on the basis of the strength of the revetment. Boers et al. (2011) reported on dune erosion in combination with hard structures. The experimental test included two physical model configurations of dunes: dunes and dune revetments. Based on observations from the model tests, it was found that fixed structures can give rise to concentration of wave loading which may lead to excess local dune erosion. Van Thiel de Vries (2012) conducted a series of physical model tests to explore the morphological impact of revetments with different heights and constant hydrodynamic conditions and water level. It was found that the overtopped waves scarped the dune face above the revetment and the eroded sediment deposited in front of the revetment creating a berm. For cases with no collapsing revetment, the created berm affected wave run-up characteristics. Figlus et al. (2015) presented the morphological changes of a sand dune and three sand dune-covered core alternatives (rubble-mound revetment, clay levee, and T-wall) under wave conditions with no overtopping. These results indicated that all the core alternatives reduced the erosion of the dune compared to a plain dune. On the wave – dune interaction investigation, D'Alessandro et al. (2012) completed a large-scale laboratory experiment to observe the time variation of the dune profile under given wave attack, and to investigate its dependency on wave height, wave period and storm surge level. It was found that erosion volume and dune face recession distance increased for large peak periods T_p in accordance with Van Gent et al. (2008) and water level, h. In addition, the comparison made between observed values of eroded volume and calculated volumes from the analytical model proposed by Larson et al. (2007) showed good agreement. Experimental data on beach profile evolution have also been used to calibrate and validate the numerical model CSHORE (Kobayashi, 2007). The model predicted the foreshore and dune profile evolution with reasonable accuracy under the collision regime and minor overwash. The comparison of measured and computed dune profiles was poor during overtopping-overwash conditions requiring model improvements for such cases.

1.2 Current Research Objective

Designing a hybrid structure where hard and soft engineering approaches are combined into one system is a challenging task due to the lack of design formulae related to wave run-up and wave overtopping for such systems. In addition, limited data are available on the hydrodynamic and morphodynamic performance of such systems in response to waves and storm surge. This triggered the ongoing research to assess both the morphodynamic performance and the hydrodynamic response of hybrid coastal structures consisting of a rubble mound breakwater covered by a sand layer in extreme wave climate conditions. The present experimental work discussed in this paper aims to investigate cross-shore profile evolution and dune erosion under specific hydrodynamic forcing condition. The effect of “core structure” slope on the morphological changes and hydrodynamic performance (i.e. overtopping, and reflection) of the hybrid system is investigated as well.

2 Experimental Setup

The proposed experimental investigation was conducted at the Haynes Coastal Engineering Laboratory of the Ocean Engineering Department at Texas A&M University. It has a shallow water wave basin with dimensions: 36.6 m in length, 29 m in width, and 1.2 m in depth. The 48-paddle wave generation system is designed to generate directional waves of 30° plus or minus from the 0° angle perpendicular to the piston-type segmented wave maker. The lab facility is equipped with a data acquisition system controlled by LabView software (National Instruments). A 3-ton overhead crane extends the width and length of the wave basin for lifting models or heavy materials into the wave basin. A side view, along the length of the wave basin, for the experimental setup in the wave basin is shown in Fig. 1-a.

2.1 Reinforced Dune Physical Model

The model of the rubble mound breakwater was scaled using Froude similarity laws with a Froude scaling factor of 1:10 selected as to satisfy the geometrical limitation of the wave basin facility. The rubble mound structure was built of rocks with an average density of ρ = 2.65 g/cm^3. The hybrid system consisted of four layers: (1) an impermeable core made of concrete blocks, (2) a filter layer (rock size, d_{50} = 6.1 cm), (3) an armor layer (rock size, d_{50} = 13.2 cm), and (4) sand layer cover with thickness ≈ 17 cm (Fig. 1-b). The entire beach section is 15.2 m in alongshore length and was divided into two sections. One section had a beach slope of 1v: 2h representing a steep slope beach section and the other section is a beach of a slope of 1v: 3h representing a mild slope beach section (Fig. 1-c).

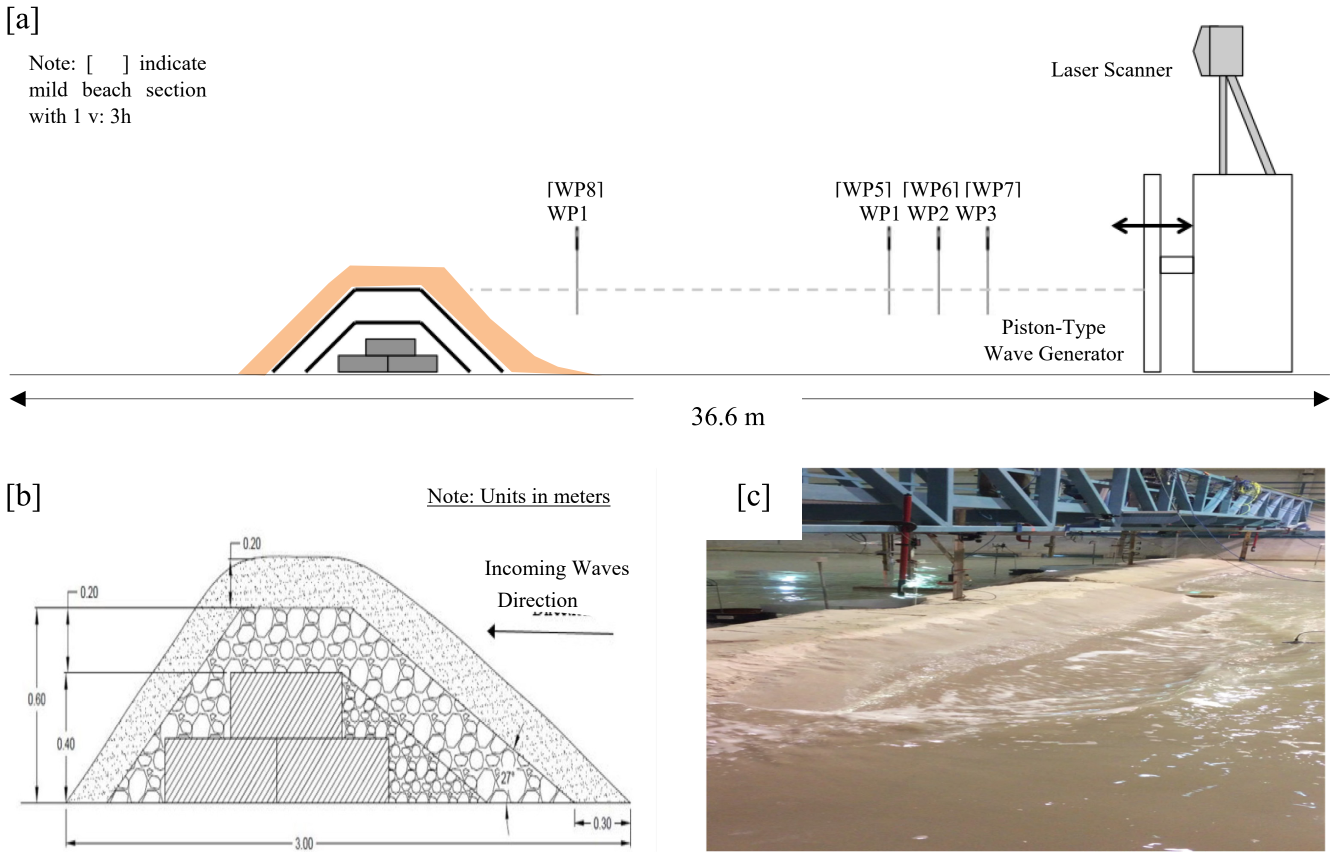

Fig. 1. (a) Schematic side view of wave basin setup, (b) Hybrid model cross-section, (c) A snapshot of the two beach sections during wave impact test.

2.2 Instrumentation

The main focus here is on the morphological response of the hybrid system to water level changes and wave forcing. Capacitance wave gauges were deployed at four locations to measure the free surface elevation above the Mean Water Level (MWL) as shown in Fig. 1-a. Three wave gauges were placed offshore to separate the incident and reflected wave trains. One wave gauge was located close to the dune toe to capture incident wave transformation (i.e. breaking) in the surfzone (Fig. 1-a). The subaerial beach section was scanned using pulsed, high-speed laser scanner (Leica Scanstation 2), with survey-grade accuracy, range and field of view (Horizontal 360^o and Vertical 270^o). This laser scanner is equipped with an integrated high-resolution digital camera with scan resolution of less than 6 mm. Several scans were taken for the initial beach profile and after each subsequent test.

2.3 Testing Conditions Setup and Analysis Method

The model test setup was arranged to observe dune erosion, overwash and breaching with increased surge levels during storm impact. The wave generator was used to generate irregular waves, based on a JONSWAP spectrum with peak enhancement factor, $\gamma = 3.3$. The duration of a single wave run was 10 minutes with significant wave height, $H_s = 0.15$ m and peak wave period, $T_p = 2.5$ sec to generate at least 200 waves per run. The experiment setup resembled a scenario of a sloped hard structure overlaid by a sand cover with increasing water depth, h, with the lower value of $h = 0.38$ m and the upper value of $h = 0.51$ m to simulate rising storm surge conditions. A total of 7 test runs with normal wave attack and 8 test runs with oblique wave attack were run for the purpose of the physical model tests (Table 1). The oblique wave attack tests were limited to be in the direction of the steep beach section instead of the mild beach section due to testing facility time limitation and availability. The laser scanner provided 3D scans of the physical hybrid model. These scans were processed and 2D cross-shore profile transects were selected (two from each beach) as a representation of dune profile evolution as will be shown in the results and discussion sections.

Tab. 1. Hydrodynamic forcing conditions for the reinforced model investigation.

Test Run	H_s *(m)*	T_p *(sec)*	Angle *(°)*	Water Depth *(m)*	Cumulative Test Duration *(min)*	Test Run	H_s *(m)*	T_p *(sec)*	Angle *(°)*	Water Depth *(m)*	Cumulative Test Duration *(min)*
1	0.15	2.5	0	0.38	10	8	0.15	2.5	25	0.38	10
2	0.15	2.5	0	0.38	20	9	0.15	2.5	25	0.38	20
3	0.15	2.5	0	0.38	30	10	0.15	2.5	25	0.38	30
4	0.15	2.5	0	0.41	40	11	0.15	2.5	25	0.41	40
5	0.15	2.5	0	0.43	50	12	0.15	2.5	25	0.43	50
6	0.15	2.5	0	0.45	60	13	0.15	2.5	25	0.45	60
7	0.15	2.5	0	0.48	70	14	0.15	2.5	25	0.48	70
-	-	-	-	-	-	15	0.15	2.5	25	0.51	80

3 Results and Discussion

3.1 Wave Reflection Analysis

The reflection coefficient, C_r is calculated based on the reflected and incident wave spectra separation using the three-probe method outlined by Mansard and Funke (1980). The C_r values for normal and oblique wave attack are plotted for different test runs in Fig. 2. For normal wave attack, the C_r values are higher for the steep beach section than for the mildly sloping beach section for Test 1 and 2, mainly due to the beach slope effect. As the initial dune profile is transformed to an equilibrium profile and with increased surge level, both beach sections are shown to behave similarly in reflecting incoming waves (Test 4 to Test 7). During oblique wave attack, both beach sections behaved differently in reflecting incoming waves due to both beach slope effect and wave directionality. Increased surge level caused excessive dune lowering and complete erosion of the dune crest (case of steep beach section). The C_r value was reduced by 30% in Test 15 compared to Test 8.

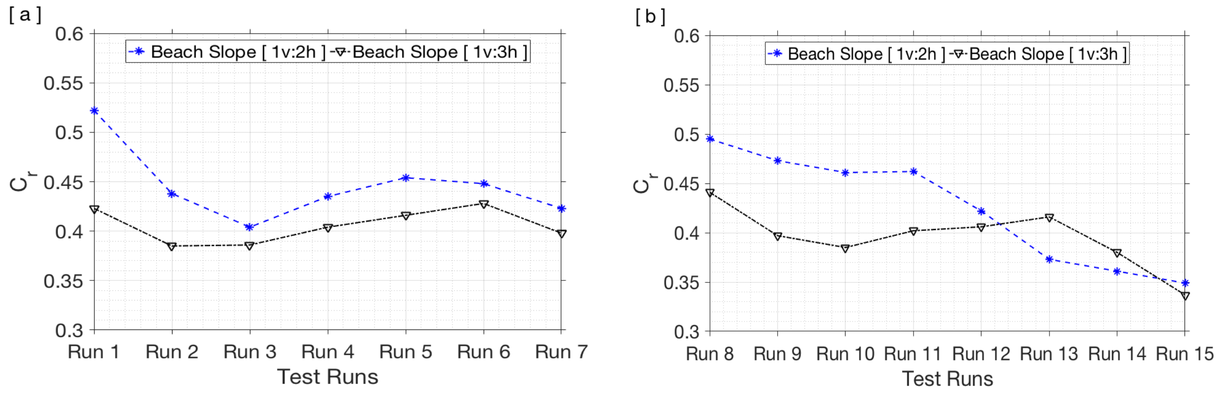

Fig. 2. Reflection Coefficient, Cr, for both beach sections in different test runs (a) Shore normal wave attack, (b) Oblique wave attack.

3.2 Reinforced Dune Profile Evolution

Sallenger et al. (2003) describe four regimes of wave dune-dune interaction, 1) swash zone with wave run-up confined to the foreshore; 2) collision regime with swash and run-up on the dune face; 3) Overwash with waves overtopping the dune crest and 4) breaching and inundation. During the collision regime, in the current experimental investigation, the incident waves reached the dune face and runup the dune. Sediment eroded from the dune face and was transported in the offshore direction. Incoming breaking waves interacting with reflected broken waves generated a superimposed wave causing the dune face to retreat under wave impact (Fig. 3 a – b). As the water level was increased, the waves continued to erode the dune face causing big lumps of sediment to slump down into the swash zone. Then, swash processes were able to move the sand seaward creating an offshore bar/step and intense wave breaking occurred (Fig. 3 a – b). The newly developed offshore bar became a prominent feature of a new cross-shore profile (Fig. 3 a – b). The top rock layer of the rubble mound structure was quickly exposed after the initial tests in the steeper sloped beach section. Along with the newly developed foreshore, this aided in dissipating the incoming wave energy and reduced the wave run up on the dune. The last test with normal wave attack yielded the overwash regime and resulted in excessive dune lowering and complete erosion of the dune crest (Fig. 3-b) with landward movement of overwashed sand. Beach profile evolution under oblique wave attack showed an erosion pattern similar to that of the normal wave attack in the case steeper sloped beach section (Fig. 3-c). Due to wave directionality tests limited to the steeper sloped beach section, the mildly sloped beach section only experienced the swash zone regime with wave runup confined to the dune face and the progressive dune face erosion was a result of surge level increase but to a lesser impact than that of the adjacent steeper sloped beach section (Fig. 3. d).

3.3 Reinforced Dune Retreat Rate and Erosion

The reinforced dune face retreat rate is calculated for cross-shore profile transects during storm surge simulation. The calculated dune scarp retreat rate for selected profile transects with respect to the initial dune profile for normal and oblique wave attack is shown in Fig 4. a-b. For the normal wave attack, the dune scarp retreat rate increased initially during the first 10 minutes of the surge simulation, which indicates dune profile adjusted to an equilibrium profile (Fig. 4-a). As the surge level increased (from Run 3 onwards), the dune scarp retreated gradually in both transects of the modeled beaches (Fig. 4-a). Towards the end of the simulation, the profile transect from the milder sloped beach experienced larger scarp retreat rates (0.108 m/min) than the steeper sloped beach section retreat (0.065 m/min), thus revealing the effect of seaward dune slope on reinforced dune scarp retreat rate. For oblique wave attack directed towards the steeper sloped beach section, the profile transect experienced a larger dune scarp retreat rate (0.11 m/min) than the case for the same profile under normal wave attack at the end of the surge simulation (Fig. 4-b). This leads to the wave

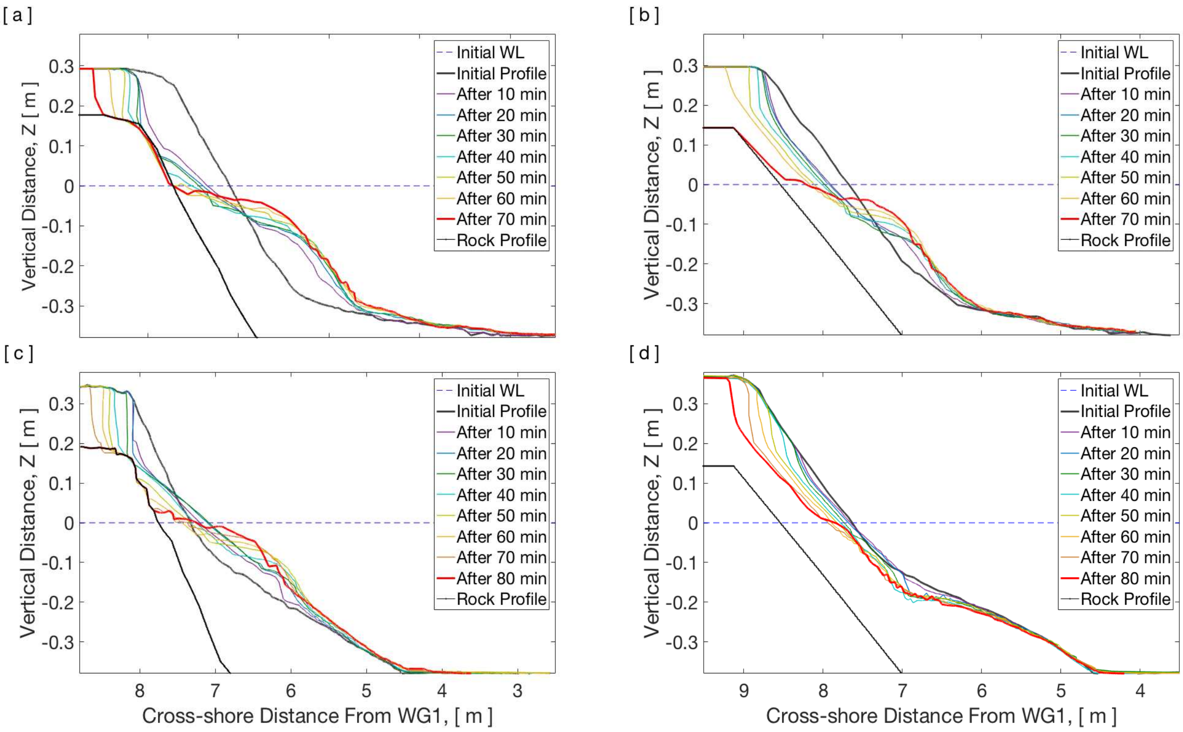

Fig. 3. Measured profile evolution of the reinforced dune model for selected profiles, (a) steep beach section with normal wave attack, (b) mild beach section with normal wave attack, (c) steep beach section with oblique wave attack, and (d) mild beach section with oblique wave attack.

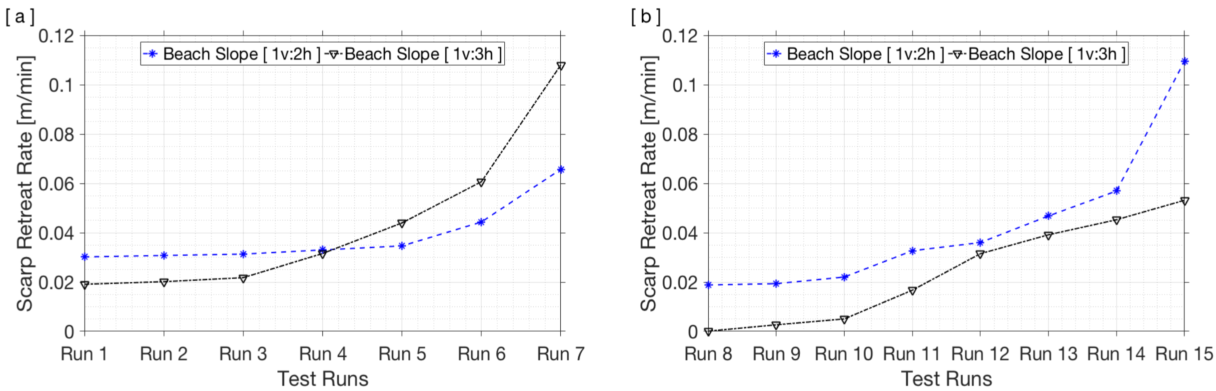

Fig. 4. Dune scarp retreat rate for selected transects during (a) normal wave attack, and (b) oblique wave attack.

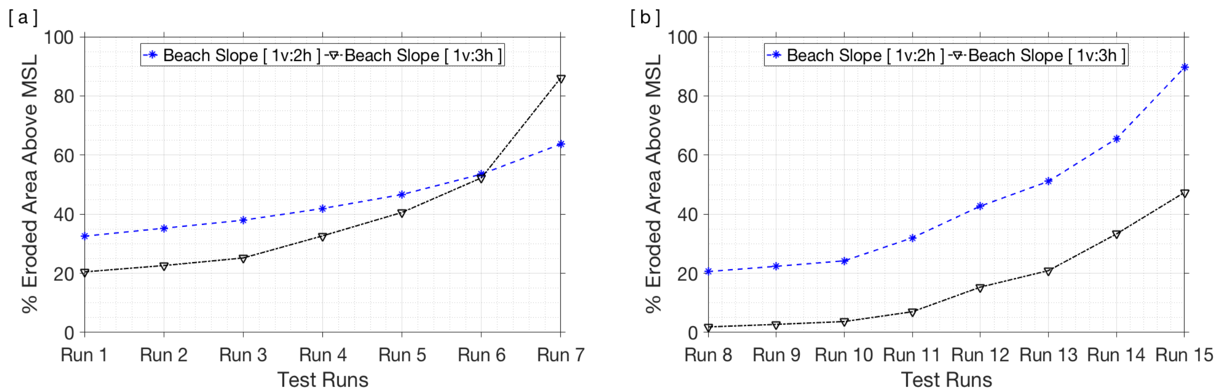

Fig. 5. Percent Eroded area for selected transects during (a) normal wave attack, and (b) oblique wave attack.

directionality influences the dune scarp retreat rate during surge simulation for the reinforced dune model. The percentage-eroded area for the surge simulation of the reinforced dune model is calculated relative to the initial available area above mean water level. In a similar manner for dune scarp retreat rate, the percentage-eroded area for cross-shore profile transects selected is shown to increase with surge level increase (Fig. 5). For the normal wave attack case, the milder sloped beach section experienced overall larger dune erosion (86%) than the steeper sloped beach section (63%). In addition, the percent overall reduction in dune area for the steeper sloped beach section is 41% larger in the case of oblique wave attack than the case of normal wave attack. Both seaward slope and wave directionality affected dune erosion above the still water level during surge simulation; however, they are considered secondary factors compared to surge level increase.

4 Conclusion

The present paper discussed the results of a three-dimensional physical model study carried out in a wave basin for a reinforced dune consisting of a rubble mound hard structure covered by a layer of sand. The main objective is to investigate the cross-shore profile evolution and dune erosion under specific hydrodynamic forcing conditions. The effect of dune seaward slope on the morphological changes of the modeled profile and the hydrodynamic performance (i.e. wave reflection) of the hybrid system is investigated as well. A comparison between the cross-shore beach profiles of the modeled beach showed that storm surge progression strongly affected the erosion process and the associated coastal profile evolution in the cross-shore direction. Eroded sediment moved offshore creating a submerged bar during the collision regime in the early stages of the storm simulation. This new profile was efficient in dissipating energy of incoming waves. The surge level is found to be the main factor that contributes to reinforced dune profile evolution during storm conditions compared to secondary factors including seaward dune slope and wave directionality. The preliminary results presented in the paper will be used for further testing and analysis aiming at a better understanding the hydrodynamic and morphological response of hybrid coastal structures and to improve numerical modeling capabilities for such situations.

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References

Anthony, E.J., Gratiot, N., 2012. Coastal engineering and large-scale mangrove destruction in Guyana, South America: Averting an environmental catastrophe in the making. Ecological Engineering 47, 268–273.

Boers, M., Van Geer, P., Van Gent, M., 2011. Dike and dune revetment impact on dune erosion, in: The Proceedings of the Coastal Sediments 2011. World Scientific Publishing Company, pp. 810–823.

Bosello, F., Nicholls, R.J., Richards, J., Roson, R., Tol, R.S.J., 2012. Economic impacts of climate change in Europe: sea-level rise. Climatic Change 112, 63–81.

Charlier, R.H., Chaineux, M.C.P., Morcos, S., 2005. Panorama of the History of Coastal Protection. Journal of Coastal Research 79–111.

D'Alessandro, F., Tomasicchio, G.R., Musci, F., Ricca, A., 2012. Dune Erosion Physical, Analytical And Numerical Modelling. Coastal Engineering Proceedings 1, 32.

Figlus, J., West, N., Almarshed B., Jonkman Sebastiaan N., 2015. Conceptual Design and Physical Model Study of Core-Enhanced Dunes as Hybrid Coastal Defence Structures. Coastal Structures and Solutions to Coastal Disasters 2015, Proceedings 65–73.

FitzGerald, D.M., Fenster, M.S., Argow, B.A., Buynevich, I.V., 2008. Coastal Impacts Due to Sea-Level Rise. Annual Review of Earth and Planetary Sciences 36, 601–647.

Griggs, G., 2005a. California's retreating coastline: where do we go from here?, in: Magoon, O.T., Convers, H., Baird, B., Miller-Henson, M. (eds.), California and the World Ocean, Conference '02 Revisiting and Revising California's Ocean Agenda. American Society of Civil Engineers, 121–125.

Griggs, G.B., 2005b. The Impacts of Coastal Armoring 73, 11.
IPCC report., 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
Kobayashi N., Agarwal A., Johnson D., 2007. Longshore Current and Sediment Transport on Beaches. Journal of Waterway, Port, Coastal, and Ocean Engineering 133, 296–304.
Larson, M., Kraus, N.C., Connell, K.J., 2007. Modeling sediment storage and transfer for simulating regional coastal evolution, in: Coastal Engineering 2006. World Scientific Publishing Company, pp. 3924–3936.
Mansard, E.P.D., Funke, E.R., 1980. The Measurement Of Incident And Reflected Spectra Using A Least Squares Method. Coastal Engineering Proceedings 1.
Nordstrom, K.F., Lampe, R., Vandemark, L.M., 2000. Reestablishing Naturally Functioning Dunes on Developed Coasts. Environmental Management 25, 37–51.
Parris, A., Bromirski, P., V, B., D, C., M, C., J, H., Horton, R., Knuuti, K., Moss, R., Obeysekera, J., A, S., Weiss, J., 2012. Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1.
Rippon, S., 2000. The Transformation of Coastal Wetlands: Exploitation and Management of Marshland Landscapes in North West Europe During the Roman and Medieval Periods. Oxford University Press.
Scavia, D., Field, J.C., Boesch, D.F., Buddemeier, R.W., Burkett, V., Cayan, D.R., Fogarty, M., Harwell, M.A., Howarth, R.W., Mason, C., Reed, D.J., Royer, T.C., Sallenger, A.H., Titus, J.G., 2002. Climate change impacts on U.S. Coastal and Marine Ecosystems. Estuaries 25, 149–164.
Slott, J.M., Murray, A.B., Ashton, A.D., Crowley, T.J., 2006. Coastline responses to changing storm patterns. Geophysical Research Letters 33.
van Gent, M.R.A., van Thiel de Vries, J.S.M., Coeveld, E.M., de Vroeg, J.H., van de Graaff, J., 2008. Large-scale dune erosion tests to study the influence of wave periods. Coastal Engineering 55, 1041–1051.
Vries, J. van T. de, 2012. Dune Erosion Above Revetments. Coastal Engineering Proceedings 1, 95.
Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.-R., 2005. Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment. Science 309, 1844–1846.