EROSION PROGRESSION OF WOODED COASTAL DUNE

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Active plantation of woody plants over coastal sand dunes has been known to reduce the wave overtopping and overwash. In this study interactions among waves, sand dune and woody plants were investigated experimentally. Wooden plants were represented by cylindrical wooden dowels. Two tests were conducted to examine the placement density of the dowels. Additional two tests were conducted to examine the toppling effect of the dowels covering the dune. The measured data indicate that toppling of the dowels on the foreslope of the dune diminishes the effectiveness of the dowels in reducing dune erosion and overwash because the dowels on the foreslope reduced wave uprush and overtopping. The data collected in these experimental study were used to calibrate and verify the numerical model CSHORE.

Keywords: vegetation; dune; erosion; toppling

INTRODUCTION

Woody plants covering sandy coastal dunes has been shown to perform as an absorbers of energy exerted by storm surges and waves. Gralher et al. (2012) conducted five tests in a laboratory experiment to examine the effects of woody plants on erosion and overwash of high and low dunes where cylindrical wooden dowels were used to represent woody plants. The dowels placed on the foreslope and backslope of the high dune were effective in reducing dune erosion and delaying wave overtopping and overwash. The dowels were observed to retard wave uprush on the foreslope but increased offshore sand transport from the eroded dune (Kobayashi et al. 2013). Experimental data collected in these tests was compared with the data predicted by using CSHORE (Kobayashi et al., 2010) which was expanded by Ayat and Kobayashi (2013) to include the vegetation effects on the hydrodynamics and sand transport. In the aforementioned study, CSHORE is expanded to include the drag force acting on the dowels. The expanded model is compared with the previous five tests and the drag coefficient is calibrated. Although observations of the effect of dowels on the erosion of sand dunes in the experiment by Gralher et. al. (2012) are interesting, the experiment was limited to the specific diameter, height, spacing, alignment and burial depth of rigid wooden dowels without toppling. To quantify the effectiveness of the density and the toppling of dowels in reducing dune erosion and overwash, four additional tests were devised by using calibrated model. These tests were conducted in the University of Delaware Wave Flume and presented in this study.

EXPERIMENTS

The experimental setup used during the vegetated dune overwash experiment was illustrated in Figure 1. This experimental setup was the same as that used by Gralher et. al. (2012). The UD wave flume is 30 m long, 1.15 m wide and 1.5 m high. The sand beach in the flume consisted of well-sorted fine sand with a median diameter of 0.18 mm. The measured specific gravity, porosity and fall velocity were 2.6, 0.4 and 2.0 cm/s, respectively. A 400-s irregular wave train with a TMA spectral shape was generated by the piston-type wave maker located at the offshore end of the flume in a water depth of 1 m. The spectral significant wave height and peak period were approximately 18.3 cm and 2.6 s, respectively. To measure the cross-shore and temporal variations of the free surface elevation during each 400-s wave burst, eight capacitance wave gauges were used. The fluid velocities in the surf zone were measured by three acoustic Doppler velocimeter sensors (one 2D ADV and two Vectrinos). Obtaining high resolution measurements of profile changes and erosion progression was crucial for this research. In order to obtain accurate profile data, a state-of-the-art profiling system consisting of a class III laser line scanner system in conjunction with a class II laser distance finder was used in the region of the rapid changes after lowering the water level. The laser line scanner system was mounted on a cart controlled by a servo motor with continuously adjustable speed. Since the bottom profile changes were minor outside the surf zone, the offshore part of the profile was measured by using an array of three ultrasonic thickness gauges. This method reduced the water level lowering to measure the entire beach profile. A vertical wall was located at the cross-shore coordinate x= 19.9 m in Figure 1 and its crest

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elevation was 6 cm above the still water level (SWL). Overtopped water was collected in a water collection basin with a capacity of 1900 liters behind the vertical wall. Sand overwash rate averaged over the 400-s run was measured by using a sand trap located inside the water collection basin.

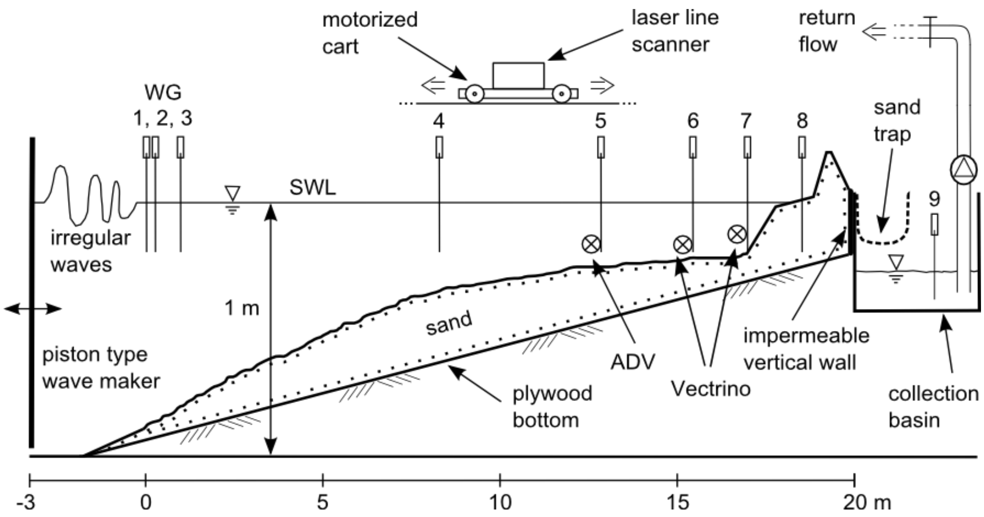

Figure 1. Schematic view of the experimental set-up including wave paddle, sandy beach profile on top of plywood slope, collection basin including sediment trap, water recirculation system, laser line scanner mounted to a motorized cart and location of the instruments measuring the hydrodynamics with a dune profile without wooden dowels.

Table 1 summarizes the four tests conducted in sequence. The first test HB in the Table 1 was adopted from Gralher et. al. (2012). This test of high (H) dune profile was bare (B) with no vegetation. SD and DD tests with sparsely (S) and densely (D) vegetated dunes were aimed at quantifying the density effect of the deeply (D) buried plants on the dune erosion and overwash. DF and DS tests with shallowly (S) buried and finitely (F) buried plants were aimed at observing the effect of plant toppling on the dune overwash and erosion. Each test comprised a number of runs of the same 400-s bursts of irregular waves impinging on the high dune. The initial profile of the high dune was the same for all the tests in Table 5 where the dune crest elevation was 21 cm above SWL and the foreslope and backslope of the dune were 1/2 and 1/3, respectively. HB test was terminated after 6 runs when the dune crest was lowered to the elevation of the wall crest. Cylindrical wooden dowels were used to represent woody plants for the four vegetated dune tests. The diameter and length of each dowel were 0.9 cm and 30 cm, respectively. Each dowel was placed vertically with a burial depth of 20 cm for the deep burial depths. The cross-shore and alongshore spacing of the dowels were 6 cm and 4.24 cm for SD and DD tests, respectively. The burial depth of each dowel was checked after each run and adjusted to 20 cm at the beginning of all runs to avoid toppling during SD and DD tests. The dowel height and burial depth were allowed to change as the bottom elevation at given cross-shore location changed with time during DS and DF tests where the dowel length was reduced to 15 cm for toppling. The cross-shore distance of the vegetation zone from the vertical wall was 80 cm (between x=19.1 and 19.9 m in Figure 1) for all the vegetated dune tests. This dowel zone covered both the backslope and foreslope. Kobayashi et. al (2013) reported that this wide dowel zone reduced the foreslope erosion and scarping significantly mainly because of the reduced wave uprush velocities by the dowels.

Table 1. Summary of Bare and Four Vegetated Dune Tests

Test	Dowel Density	Burial Depth	Number of Runs	Total Duration (s)
HB*	No Vegetation	-	6	2400
SD	Sparse	Deep	8	3200
DD	Dense	Deep	29	11600
DF	Dense	Finite	9	3600
DS	Dense	Shallow	6	2400

*from Gralher et. al. (2012)

For each run, the free surface elevation (η) above SWL was measured by wave gauges WG1 – WG8 located at the onshore coordinate x = 0.0, 0.25, 0.95, 8.3, 12.9, 15.5, 17.1 and 18.6 m along the centerline of the flume where the vertical wall was located at x = 19.9 m. The fluid velocities were measured at x = 12.9, 15.5 and 17.1 m at an elevation of 1/3 of the local water depth above the bottom in the vicinity of the flume centerline. The measured 400-s time series sampled at 20 Hz were reduced by removing the initial 20-s transition period before the data analysis. The 380-s time series from WG1 – WG3 were used to separate incident and reflected waves at the location of WG1. The incident waves are represented by the spectral significant wave height H_{mo} and peak period T_P as well as the significant wave height H_S and period T_S. The reflection coefficient, R is defined as the ratio between the values of H_{mo} for the reflected and incident waves. Table 2 lists the average value of these wave parameters at x=0 for all the runs in each test. The value of R decreased slightly with the decrease of the foreslope slope during each test.

Table 2. Incident Wave Characteristics at x=0 for Four Tests

Test	H_{mo} (cm)	H_S (cm)	T_P (s)	T_S (s)	R
HB*	18.61	18.30	2.65	2.27	0.16
SD	18.31	18.08	2.57	2.32	0.16
DD	18.21	17.96	2.57	2.30	0.16
DF	18.26	17.97	2.57	2.30	0.16
DS	18.30	18.02	2.57	2.31	0.17
*from Gralher et. al. (2012)					

The measurements for all the runs in all the tests were analyzed to examine the effects of the plant density difference and the plant toppling on the dune and beach profile evolution, wave hydrodynamics, and overwash.

SPARSELY AND DENSELY WOODED DUNE TESTS

The dowel height d=10 cm and burial depth d_b=20 cm were kept the same for these deep (D) burial tests of no toppling. The number of runs for SD and DD tests were 8 and 29, respectively, for the dune crest lowering to the level of the vertical wall crest. The sparse dowels for SD test were not effective in reducing dune erosion and overwash in comparison to the bare dune test HB with 6 runs. The limited data suggest that the reduction of dune erosion and overwash by the dowels may be negligible if the dowel spacing (S) exceeds about (7b) with b=dowel diameter.

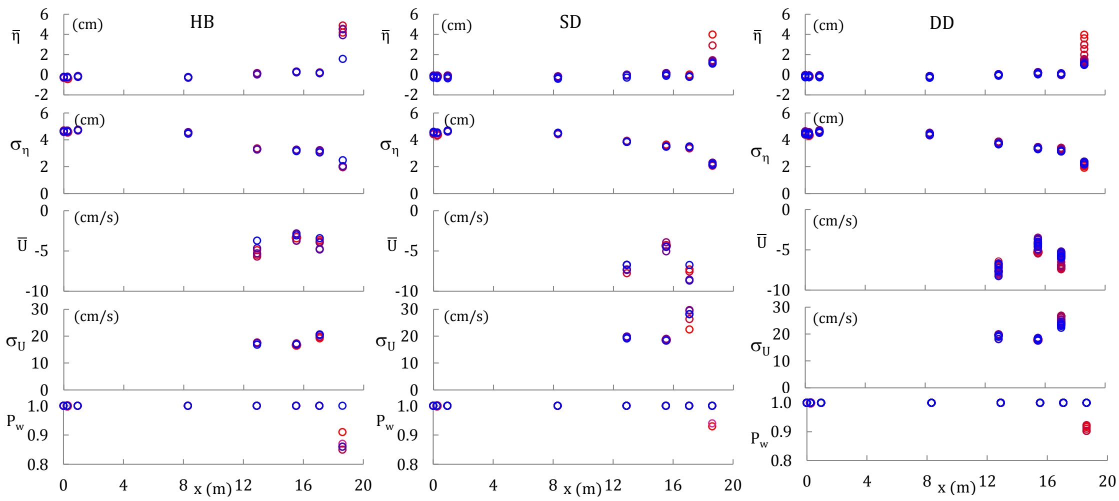

Figure 2. Measured mean and standard derivation of free surface elevation and cross-shore velocity together with wet probability P_w for HB, SD and DD tests.

The measured free surface elevation η and cross-shore velocity U were analyzed statistically to obtain the mean water level $\bar{\eta}$, standard deviation σ_η related to the spectral significant wave height $H_{mo}=4\sigma_\eta$, return current $\bar{U}$, and standard deviation σ_U representing the oscillatory wave velocity. The wet probability P_w is the ratio between the wet and total durations. The measured values for all runs in each of HB, SD and DD tests are shown in Figure 2. The vegetation effect is negligible for these hydrodynamic variables measured seaward of the vegetation zone.

Figure 3 shows the evolution of measured dune profiles for HB, SD and DD tests. The dowel density for HB test can be regarded as zero. Three thick lines are used in Figure 3 to differentiate the initial, intermediate, and final profiles in each test. The measured dune profile evolutions appear similar apart from the dowel density difference and evolution rate (run number) difference. The measured temporal variations of the wave overtopping rate q_o and overwash rate q_{bs} are shown in Figure 4 for these three tests. The average rates q_o and q_{bs} for each 400-s run are plotted at the time t corresponding to the middle of the run where t=0 at the beginning of each test. The measured q_o and q_{bs} were zero or very small until the dune crest was lowered sufficiently.

The sediment budget in the zone of x= 16-19.9 m is examined in the same way as in Kobayashi et. al. (2013). The volume change $V_c(t)$ per unit alongshore length is obtained by computing the area change of the measured profile at time t for the initial profile at t=0 and V_c is positive for erosion. The sand volume $V_o(t)$ per unit alongshore length associated with overwash is obtained by integrating q_{bs} from t=0 to time t at the end of each run where the sand porosity of 0.4 is included in V_o for the comparison of V_c and V_o. Figure 5 shows the measured time series of V_c and V_o. The small negative (deposition) values of V_c occurred when the onshore sand transport volume at x=16 m exceeded the small overwash volume V_o. The large positive values of V_c and V_o occurred at the same time and large sand overwash volume resulted in the large erosion volume in the zone of x=16-19.9 m.

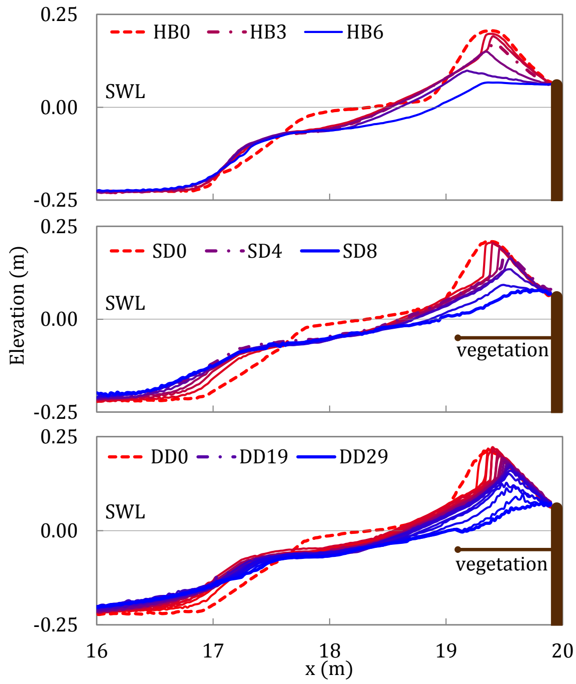

Figure 3. Measured dune profiles for HB, SD and DD tests.

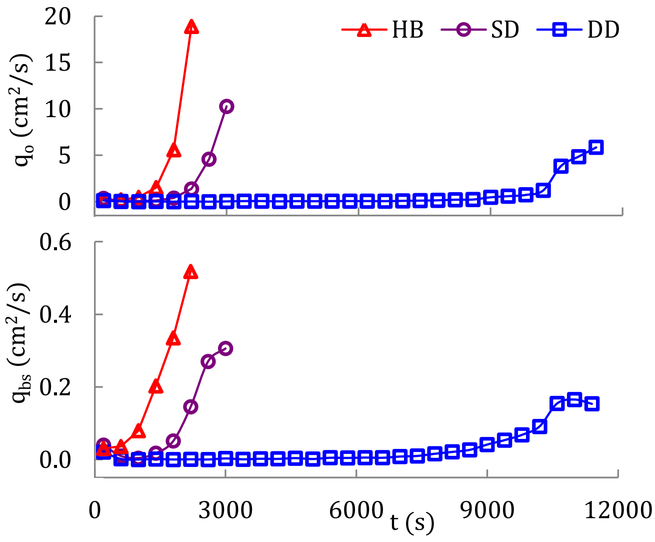

Figure 4. Temporal variations of wave overtopping rate q_o and sand overwash rate q_{bs} for HB, SD and DD tests.

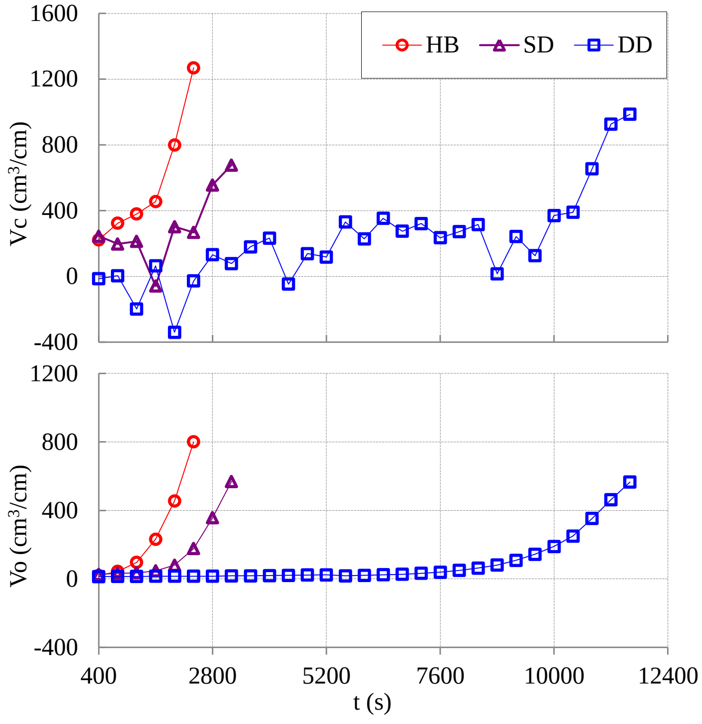

Figure 5. Temporal variations of cumulative sand volume change V_c and overwash volume V_o per unit width for HB, SD and DD tests.

WOODEN DOWEL TOPPLING TESTS

SD and DD tests were limited to the dowel height d=10 cm and burial depth d_b=20 cm throughout the tests. The dowel top was emergent above uprushing and downrushing water and no dowel toppling occurred. To allow the occurrence of dowel submergence and toppling, the 30-cm long dowel was cut in half to create two 15-cm long dowels. These short dowels were placed in the same pattern as the dense (D) dowels for DD test with the deep (D) burial depth d_b=20 cm for no toppling. Two toppling tests were conducted for the finite (F) and shallow (S) burial depths d_b=10 and 5 cm. The dowel toppling increased dune erosion and the number of runs were 9 and 6 for DF and DS tests, respectively. For DF and DS tests with (d+d_b)=15 cm, the elevations of the top and bottom of each vertical dowel were kept constant during each test. The dowel height and burial depth changed as the bottom elevation $z_b(t,x)$ at given x changed with time t during each test. The erosion depth $d_e(t,x)$ below the initial bottom elevation $z_b(t=0,x)$ is defined as $d_e(t,x)=[\ z_b(t=0,x)-\ z_b(t,x)]$ where $d_e<0$ for deposition. The actual burial depth (d_b-d_e) normalized by the dowel diameter b=0.9 cm is used to develop a simple toppling criterion.

Figure 6 shows the mean and standard deviation of η and U together with the wet probability for DS and DF tests where DD test is plotted again for the comparisons. The toppling effect was negligible for the measured hydrodynamics variables seaward of the vegetation zone.

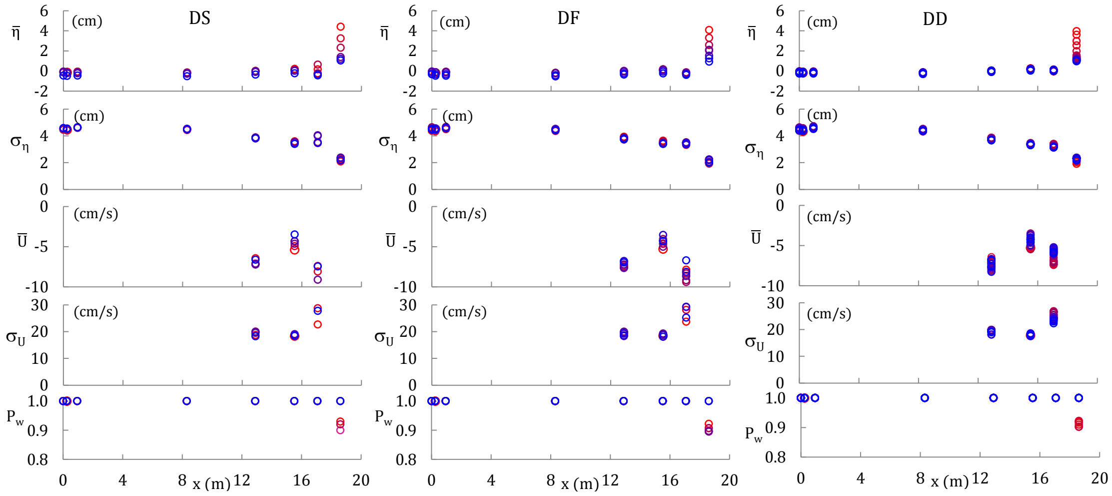

Figure 6. Measured mean and standard deviation of free surface elevation and cross-shore velocity together with wet probability P_w for DS, DF and DD tests.

Figure 7 shows the measured dune profiles for DS, DF and DS tests. The landward progression of dowel toppling and the dune crest lowering in Figure 7 are correlated positively. Both occurred faster in DS test than DF test. The dune profile evolution is influenced by the wave overtopping rate q_o and overwash rate q_{bs}. Figure 8 shows the measured temporal variations of q_o and q_{bs} for DD, DF and DS tests. The dune crest lowering accelerated when q_o and q_{bs} increased rapidly. The effectiveness of the dowels in reducing dune erosion and overwash arises mostly from the reduction of wave uprush and overtopping by the dowels on the foreslope of the dune. The dowel effectiveness diminishes after the dowel toppling on the foreslope.

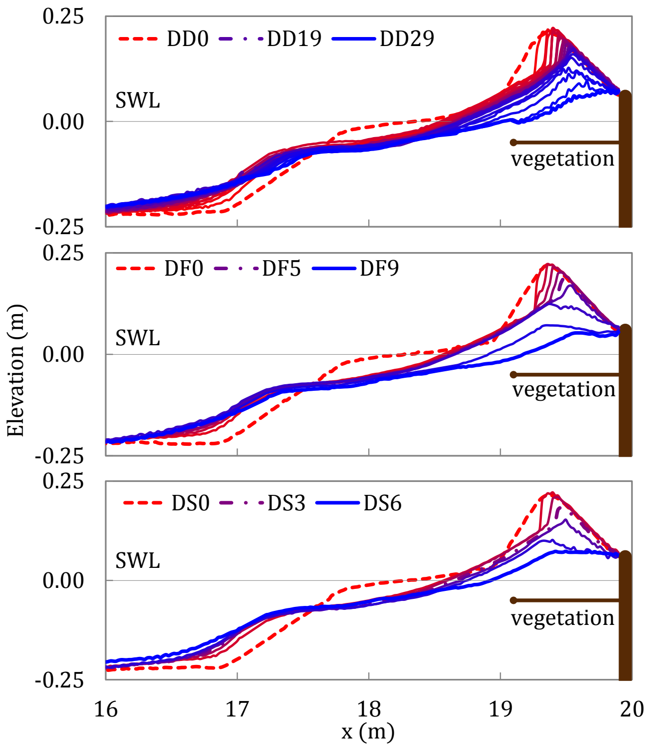

Figure 7. Measured dune profiles for DD, DF and DS tests.

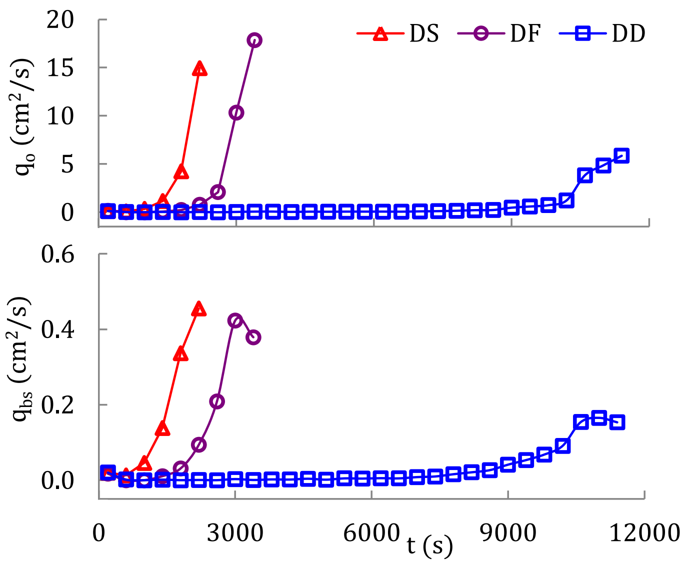

Figure 8. Temporal variations of wave overtopping rate q_o and sand overwash rate q_{bs} for DD, DF and DS tests.

Figure 9 shows the sediment budget in the zone of x=16-19.9 m for DD, DF and DS tests in the same way as in Figure 5. The plant toppling increased the sand overwash volume V_o and the erosional volume change V_c rapidly.

For the dense dowel placement of DF and DS tests, 26 dowels were place alongshore at 19 cross-shore locations. During the 400-s run, some dowels were toppled and floated in uprushing and downrushing water. After each run, the placement location of each toppled dowel was recorded. The toppled dowels were removed before the next run. The observed dowel toppling was not really uniform alongshore. Dowel toppling at each of the 19 cross-shore locations is regarded to have occurred when at least 14 out of the 26 alongshore dowels were toppled. The run number corresponding to this toppling definition is identified at each of the 19 cross-shore locations. The values of the burial depth (d_b-d_e) at given x before and after the toppling run are obtained where the bottom elevation z_b was measured at time t=0 and after each run. Figure 10 shows the values of (d_b-d_e)/b with b=0.9 cm before and after the toppling run at given x. The difference between the no toppling and toppling values is the increment of the erosion depth d_e normalized by b during the toppling run. The increase of the erosion depth during the toppling run was large on the foreslope of the dune because the overturned dowels lifted some of the surrounding sand. No toppling occurred at the 5 and 2 cross-shore locations next to the vertical wall at x=19.9 m for DF and DS tests, respectively. These locations correspond to the locations without toppling values in Figure 10. The toppling on the foreslope occurred when the value of (d_b-d_e)/b was about 9.5 and 5.5 for DF and DS tests, respectively, as indicated by the horizontal line for each test.

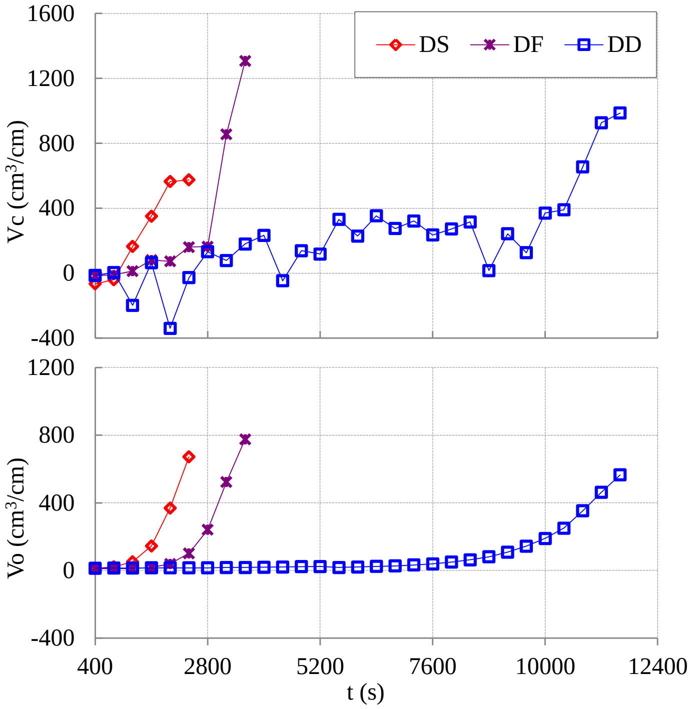

Figure 9. Temporal variations of cumulative sand volume change V_c and overwash volume V_o per unit width for DD, DF and DS tests.

Figure 11 shows the measured landward progression of dowel toppling where the toppling time t_t in the middle of the toppling run at given x for each of the 19 cross-shore dowel locations. The upper bound of t_t corresponds to the test duration of each test. The landward toppling progressed faster for DS test where the initial burial depth d_b was 5 cm and 10 cm for DS and DF tests, respectively.

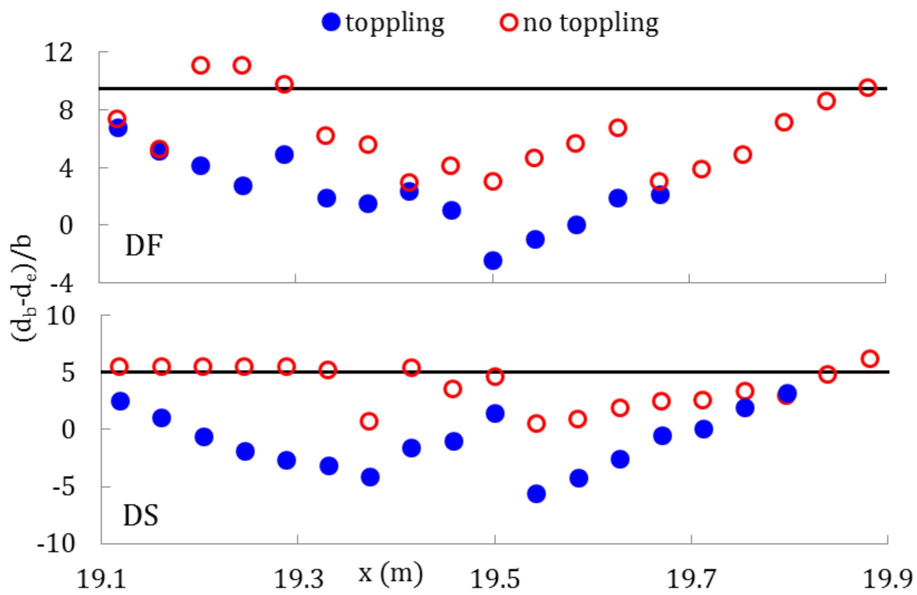

Figure 10. Burial depth (d_b-d_e) normalized by dowel diameter b before and after toppling run for DF and DS tests.

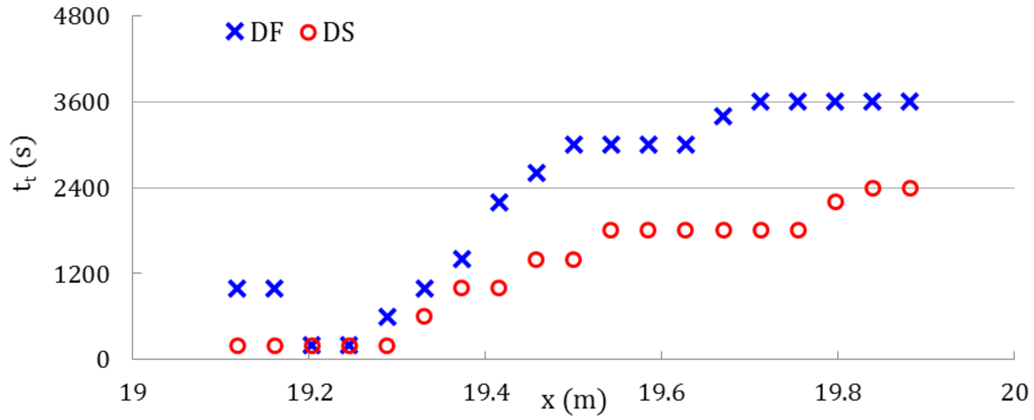

Figure 11. Measured landward progression of toppling time t_t in the middle of toppling run for DF and DS tests.

CONCLUSIONS

Two high dune tests were conducted to examine the effect of the spacing, S and density of the dowels of diameter, b covering the entire dune. The effectiveness of the dowels in reducing dune erosion and overwash diminished when the ratio S/b, became larger than about 7. Additional two tests were conducted to examine the toppling effect of the dowels covering the high dune. The measured data indicate that toppling of the dowels on the foreslope of the high dune diminishes the effectiveness of the dowels in reducing dune erosion and overwash because the dowels on the foreslope reduced wave uprush and overtopping. The measurements for SD, DD, DF and DS tests were used to calibrate and verify the numerical model CSHORE by Ayat and Kobayashi (2014).

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