PILE FENCE TO ENHANCE DUNE RESILIENCY

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A beach with a berm and dune provides storm protection but wave overtopping and overwash of the dune may lead to dune breaching and inundation. Dune erosion and overwash may be reduced by piles placed linearly along the toe of the dune. This study will explore whether piles can be used to make dunes more resilient against storm surge and waves. Six laboratory tests were conducted to observe the effect of pile fence porosity, location and pile toppling. It is recommended that a pile fence porosity of 0.5 or less be used to obtain significant increase in dune resiliency. Presence of the pile fence may increase offshore sediment transport resulting in more deposition in the surf zone. The pile fence should be placed near the dune toe to reduce wave uprush on the dune foreslope and to minimize pile toppling due to wave action.

Keywords: pile fence; wave overtopping; dune; erosion; overwash; sediment transport

INTRODUCTION

In the US, a wide berm and a high dune are maintained by periodic nourishment because a sufficient sand volume against a 100-year storm is necessary in order to reduce flooding damage. The renourishment period for nourished Delaware beaches is about three years but, in reality, the eroded beaches are repaired because of the requirement of the minimum sand volume in the berm and dune. If the minimum required sand volume of the dune can be reduced, the frequency of the repair and renourishment may be reduced as well. A relatively simple (and inexpensive) method is needed to partially protect the dune against wave uprush and overtopping and reduce dune erosion and overwash.

Fences are currently used to stabilize dunes against windblown sand transport. Coastal Engineering Manual (CEM 2002) recommends fencing with a porosity of about 0.5. The standard slat-type wooden snow fence appears to be the most practical and cost effective and has been widely used for dune stabilization and to promote dune growth. The slat-type wooden fence is not strong enough against wave uprush during a storm. This study aims to design the pile fence in such a way to reduce wave overtopping and overwash and the rate of dune crest lowering by more than 100%.

Dune erosion and overwash may be reduced by piles (dowels in the experiment) placed linearly along the toe of the dune. Pile fences are similar to wooden fences used for dune stabilization against wind but need to be strong enough to withstand wave action. Coastal structures similar to pile fences include permeable pile groins placed normal to the shoreline (Raudkivi 1996), vertical slotted barriers for reduction of transmitted waves (e.g., Isaacson et al. 1998), and pile row breakwaters placed parallel to the shoreline to restore an eroding beach (Reedijk and Muttray 2007). The linear spacing of piles or timber planks of these coastal structures is similar to those of wooden wind fences. Pile fences should be designed to function as wooden fences under normal conditions, which require a porosity of approximately 0.5. Several pile fence arrangements were tested to find efficient arrangements in reducing dune erosion and overwash using the minimum number of piles per unit alongshore length. The effects of pile toppling and fence location were also investigated.

EXPERIMENT

The experiment was conducted in the wave tank of the University of Delaware which is 30 m long, 2.5 m wide and 1.5 m high. A mid-width dividing wall along the length of the wave tank was installed to reduce the amount of fine sand, the water level change due to wave overtopping and seiching development in the wave tank. Figure 1 depicts the experimental setup in the 1.15-m wide flume which is similar to the dune overwash experiment by Gralher et al. (2012). The initial profile of the dune is depicted where the crest elevation was 21 cm above SWL and the foreslope and backslope of the dune were 1/2 and 1/3, respectively.

A piston-type wave maker in 1-m water depth generated a 400-s burst of irregular wages corresponding to a TMA spectrum. The wave maker has no capability of absorbing waves reflected from the dune. The spectral significant wave height and peak period were approximately 18 cm and 2.6 s, respectively. The sand beach placed on a plywood bottom with a slope of 1/30 consisted of well-sorted fine sand with a median diameter of 0.18 mm. The placed sand was moistened and compacted before each test. The measured specific gravity, porosity and fall velocity were 2.6, 0.4 and

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2.0 cm/s, respectively. Eight capitance wave gauges (WG1-8) were installed for the measurement of the free surface elevation along the wave tank. WG1-WG3 were offshore outside the surf zone. WG4 was located near the breaker zone. WG5-WG7 were in the inner surf zone while WG8 was located in the swash zone. One Sontek 2D acoustic Doppler velocimeters (ADV) and two Nortek Vectrinos were used to measure fluid velocities at an elevation of 1/3 of the local water depth above the bottom. A laser line scanner mounted on a motorized cart was used to record alongshore transects at 2 cm cross-shore intervals with an accuracy of ±1 mm, yielding 3D bathymetry of the entire subaerial (after lowering the water level) portion of the bed. An array of three submerged ultrasonic transducers were used to record three cross-shore transects for the submerged portion of the bed.

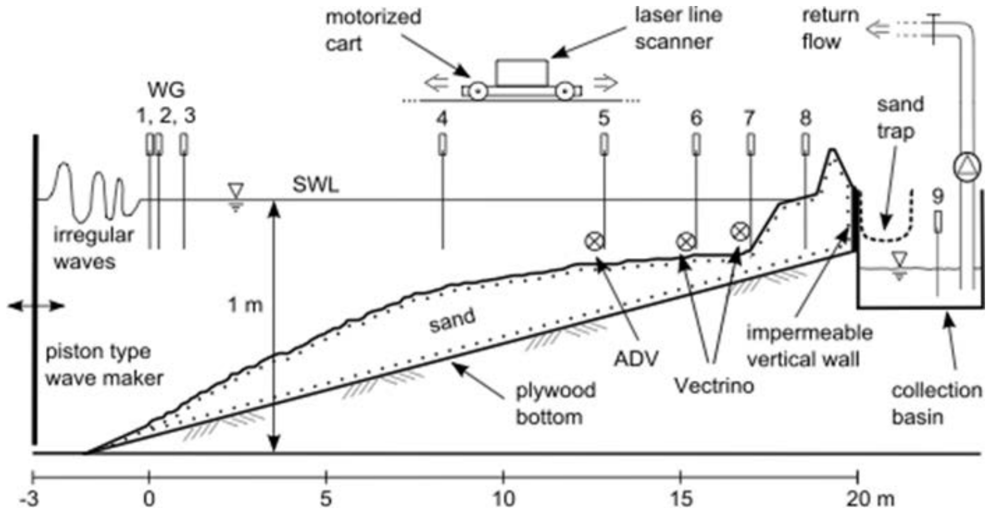

Figure 1. Schematic side view of the experimental setup including wave paddle, sandy beach profile on top of plywood slope, collection basin including sediment trap, water recirculation system, and laser line scanner mounted on a motorized card and location of the instruments measuring the hydrodynamics.

Water and sand transported over the impermeable vertical wall in Figure 1 during each 400-s run were collected in a basin. The elevation of the wall crest was 6 cm above the still water level (SWL). A sand trap made from polyester fabric mesh retained grain diameters exceeding 0.074 mm and allowed water to pass through. The trapped sand was analyzed to obtain the water content and dry sand mass. The collection basin included a water recirculation system consisting of a pump, a flow meter, pipes, and a valve to maintain a constant still water level in the 2.5-m wide tank. The water volume change in the collection basin was measured using a wave gauge (WG9) in Figure 1 and a mechanical float to ensure data accuracy. This experimental setup allowed the accurate measurement of the water overtopping rate and sand overwash rate averaged over the 400-s run.

For the experiment, cylindrical wooden dowels were placed along the toe of the dune and the configuration is characterized by the fence porosity. Porosity ε is defined as the fraction of alongshore opening encountered by uprushing water:

$$\varepsilon = \frac{S - nb}{S} = 1 - \frac{nb}{S} \tag{1}$$

where S is the center-to-center pile spacing, n is the number of rows, and b is the pile (dowel) diameter. The pile spacing, shown in Figure 2, used in the tests was either narrow (S = 2 cm) or wide (S = 4 cm) as well as single (n =1) or double (n = 2) rows. The above definition of porosity assumes that the first and second rows for n = 2 are equally effective against wave uprush. When n = 2, the dowels are placed in two staggered rows so that wave uprush through the gap of the first row was slowed down by the dowels in the second row. Dowels used in the experiment had a diameter b = 0.9 cm.

In tests where the effect of pile toppling was not analyzed ("no toppling" tests), 30 cm dowels were used to create the pile fence wherein 20 cm of the dowel was buried (d_b) and 10 cm was emerged (d_e) as shown in Figure 2. After each run, the dowels were adjusted to keep the d_b and d_e parameters constant. In tests where the effect of pile toppling was analyzed, 15 cm dowels were used with d_b = 10 cm and d_e = 5 cm. For the toppling tests, (d_b + d_e) = 15 cm but d_b and d_e were allowed to change with the evolving sand surface under wave action. These shorter dowels allowed the occurrence of dowel submergence and toppling. After each run, the location of each toppled dowel was recorded and toppled dowels were removed before the next run.

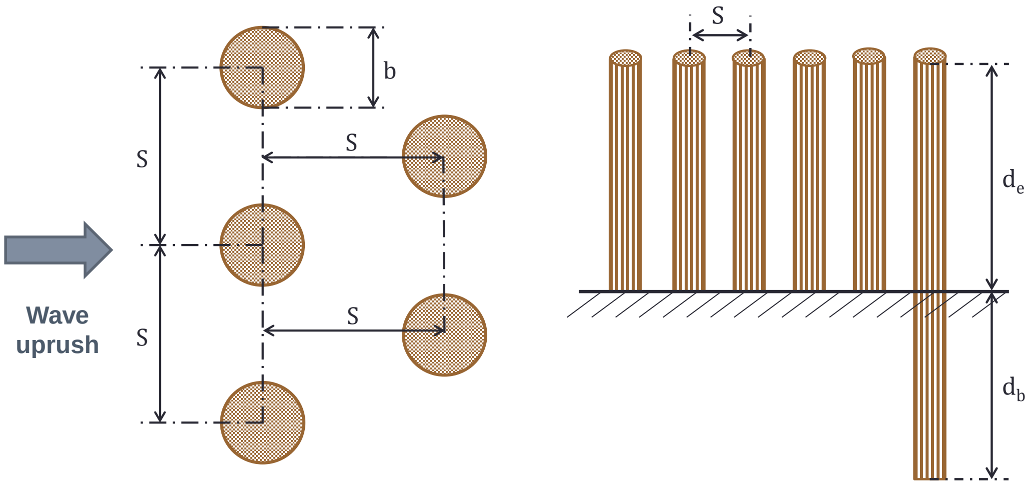

Figure 2. Pile fence spacing (n =2) (left) and schematic of dowel burial depth (d_b) and emerged height (d_e) (right).

Table 1 summarizes the six tests conducted in sequence. Each test run was comprised of the same 400-s bursts of irregular waves impinging on the dune. The six tests are categorized into three groups: narrow (N) pile spacing DN and SN tests, with double (D) and single (S) rows, respectively; wide (W) pile spacing DW and SW tests, with double (D) and single (S) rows, respectively; and pile toppling (T) tests TD and TB, with the pile fence located at the dune (D) and berm (B), respectively. The narrow and wide pile spacing tests did not allow for toppling and the pile fence for these four tests were located at a cross-shore location of x = 19.12 m on the dune foreslope where the cross-shore coordinate x is positive onshore with x = 0 m at WG1 in Figure 1. In the pile toppling tests, the pile fence of the TD test was also located on the dune foreslope and the fence of the TB test was moved to x = 18.64 m on berm where the local bottom erosion was observed to be the minimum in the TD test. Figure 3 to Figure 5 shows the initial pile fence configurations before commencement of each test.

Table 1. Summary of six tests.

Test	Number of rows	Pile spacing	Toppling	Pile location	Porosity	Number of runs
DN	Double	Narrow	No	Dune	0.1	17
SN	Single	Narrow	No	Dune	0.55	9
DW	Double	Wide	No	Dune	0.55	7*
SW	Single	Wide	No	Dune	0.78	6
TD	Single	Narrow	Yes	Dune	0.55	11
TB	Single	Narrow	Yes	Berm	0.55	8

* DW test was terminated after 7 runs due to wave maker malfunction

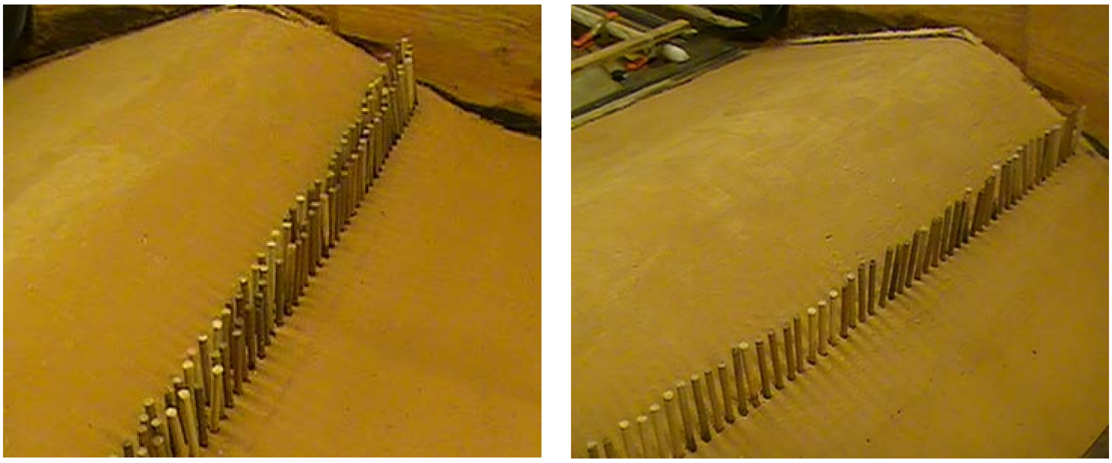

Figure 3. Pile fence configurations before the DN (left) and SN (right) tests.

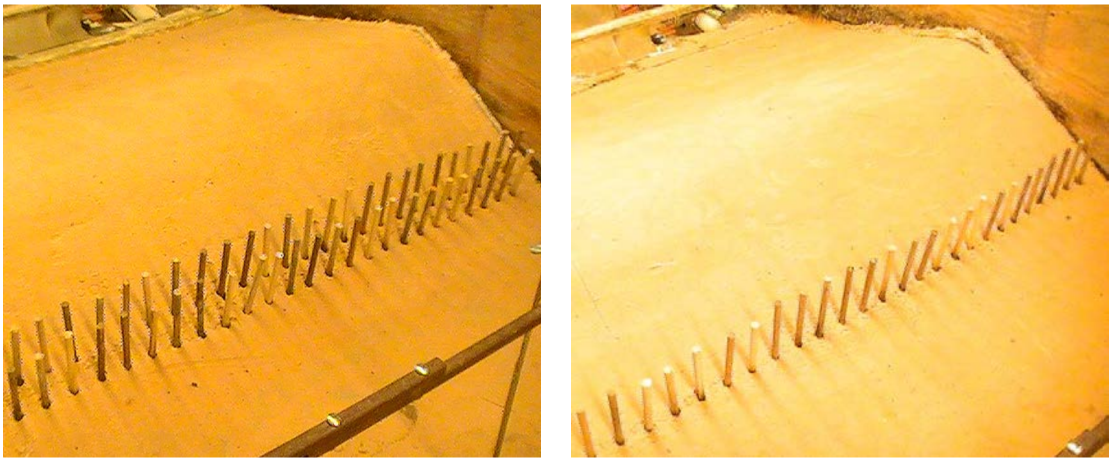

Figure 4. Pile fence configurations before the DW (left) and SW (right) tests.

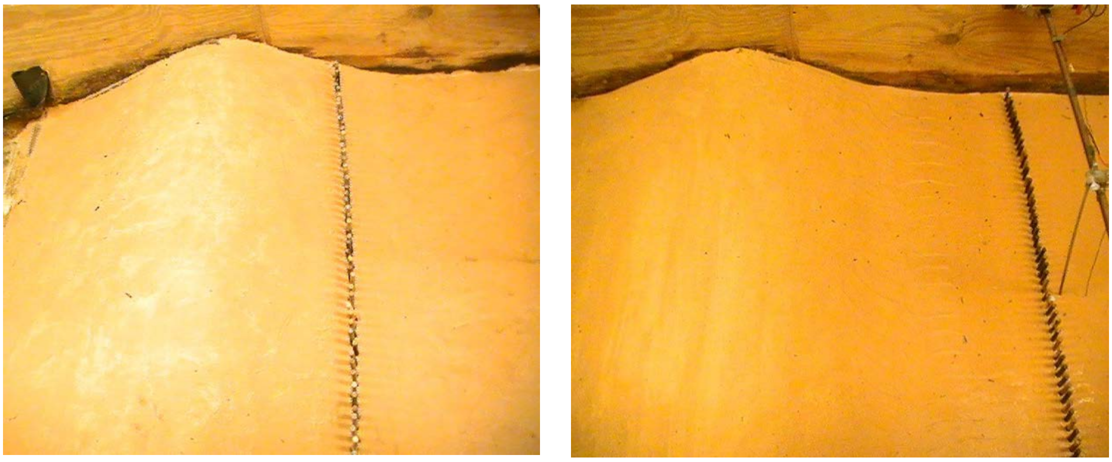

Figure 5. Pile fence configurations before the TD (left) and TB (right) tests.

The tests were terminated when the dune crest elevation reached the elevation of the impermeable vertical wall or when alongshore variability across the dune became excessive. The DW test was terminated at run 7 due to a wave maker malfunction during run 8 in which a single large wave significantly changed the bottom profile. Gralher et al. (2012) conducted a test on the same dune profile used in this experiment but without a pile fence. The test, called the HB (high bare dune) test, was terminated after run 6 when the dune crest elevation reached that of the vertical wall.

Comparisons are made to examine the differences between the HB test (ε = 1.00) and SW test (ε = 0.78).

DATA ANALYSIS

Narrow Pile Spacing Tests

Figure 6 shows the measured dune profiles for the DN and SN tests in the zone of x = 15 - 19.9 m of noticeable profile changes in front of the vertical wall. The profiles seaward of x = 15 m did not change significantly. Three thick lines are used in Figure 6 to differentiate the initial, intermediate and final profiles in each test. The location of the pile fence is indicated by a vertical dotted line. In both tests, the dune crest was lowered initially by the seaward sand transport and foreslope scarping and subsequently by wave overtopping and overwash over the vertical wall. Scarping and slumping was observed in both tests. Backslope erosion caused by wave overtopping and overwash started after DN11 and SN6, causing the wave overtopping to increase rapidly. The DN test was run until the dune crest elevation reached the elevation of the vertical wall at the end of run 17. The SN test was terminated after run 9 due to excessive alongshore non-uniformity.

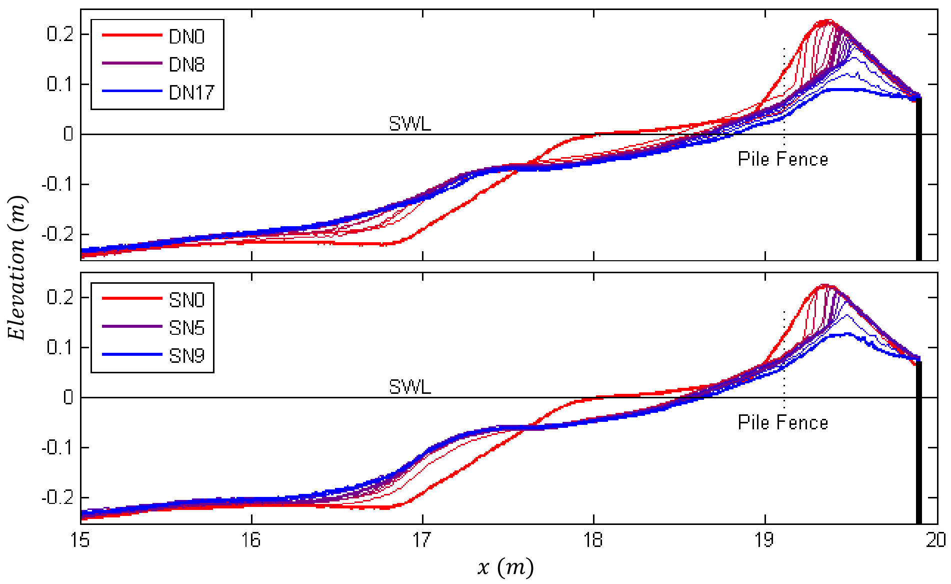

Figure 6. Dune profile evolution for DN (top) and SN (bottom) tests. The color scale from red (initial profile) to blue (final profile) indicates the measured profile number (DN: 0−17; SN: 0−9).

Figure 7 shows the mean $\bar{\eta}$ and standard deviation σ_η of the measured free surface elevation η at the eight wave gauges for the DN and SN tests. Since the statistical values were calculated over the respective duration of 400-s, the circles were plotted in the middle of each run starting from t = 0 s at the beginning of each test. The temporal variation is shown by the color scheme ranging from red for the first run to the respective final run plotted in blue. The averaging for WG8 was performed for the wet duration only because it was buried partially in the sand. The decrease of $\bar{\eta}$ at WG8 during each test was caused by the decrease of the bottom elevation associated with the berm erosion in Figure 6. The standard deviation σ_η is proportional to the spectral significant wave height, $H_{m0} = 4\sigma_\eta$. The values of σ_η at WG8 increased during each test because the berm erosion lowered the bottom elevation. Overall, with the exception of WG8, $\bar{\eta}$ and σ_η show only minor variations over time. The wet probability P_w is defined as the ratio between the wet and total durations where P_w = 1.0 at WG1 – WG7 and P_w at WG8 was approximately 0.9 initially and increased to 1.0 after the berm erosion. The P_w value of the DN test reached 1.0 more quickly than the SN tests due to the increased berm erosion in front of the less porous pile fence. The measured free surface elevation statistics for the other tests are similar and are not presented later.

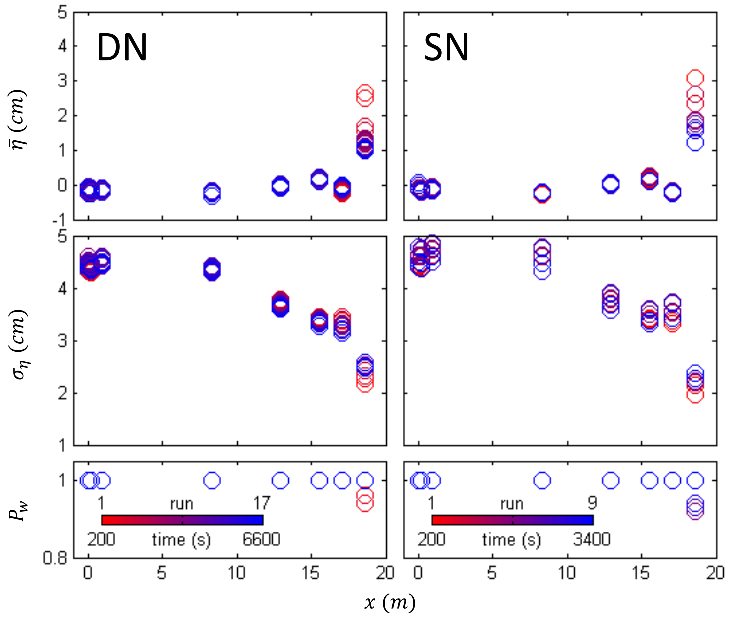

Figure 7. Cross-shore variations of the mean (top), standard deviation (middle) of the free surface elevation and wet probability (bottom) during the DN (left) and SN (right) tests.

The mean $\bar{u}$ and standard deviation σ_u of the measured cross-shore velocity u in the inner surf zone (x = 12.9 - 17.1 m) did not change significantly during each test. The cross-shore and temporal variations of the velocity statistics are shown in Figure 8 for the DN and SN tests. As explained previously, the temporal variation is represented by the color scheme ranging from red (first wave run) to blue (last wave run). The measured values of $\bar{u}$ were negative and the undertow current decreased from x = 12.9 m to x = 15.5 m before its increase at x = 17.1 m where some broken waves in the inner surf zone broke again on the steeper bottom slope (see Figure 6). The standard deviation σ_u varied little between x = 12.9 - 15.5 m and increased at x = 17.1 m possibly because of the increased wave breaking on the steeper bottom slope. Velocities do not appear to have been significantly affected by the fence configuration. It was noted that the measured alongshore and vertical velocities were small in comparison to the cross-shore velocities. The measured cross-shore velocity statistics for the other tests are similar and are not presented later.

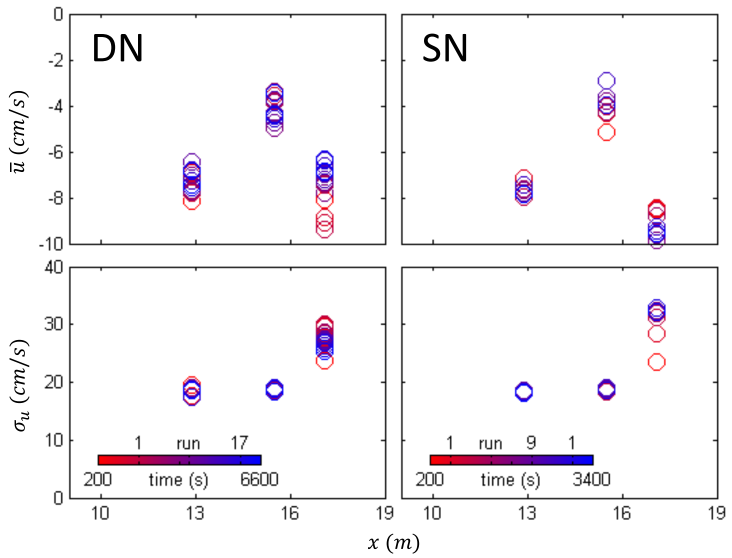

Figure 8. Temporal variations of the mean (top) and standard deviation (bottom) of the cross-shore velocity at the three velocimeters during the DN (left) and SN (right) tests.

Figure 9 shows the temporal variations of the measured wave (water) overtopping rate q_o and sand overwash rate q_{bs} for the tests. The measured rates are plotted at time t corresponding to the middle of each run. For the DN and SN tests, significant wave overtopping and overwash did not occur until DN11 and SN6, respectively. The measured rates after DN11 increased slowly relative to SN6. The double rows were more effective in reducing q_o and q_{bs}. The reduced porosity reduced wave uprush on the upward foreslope.

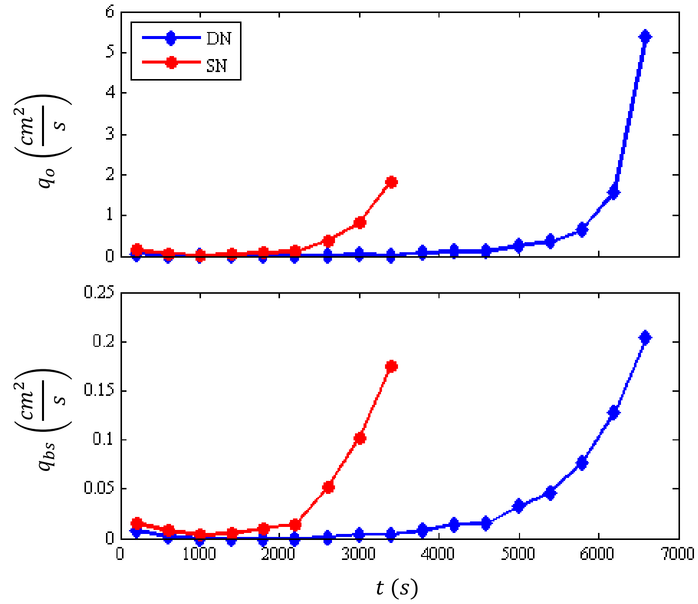

Figure 9. Temporal variations of wave overtopping rate q_o (top) and sand overwash rate q_{bs} (bottom) during the DN and SN tests.

The direction of sediment transport from the zone of x = 19.1 – 19.9 m is examined in Figure 10. This zone corresponds to the zone landward of the pile fence aligned alongshore (dune zone). The volume change V_c per unit alongshore length was obtained by computing the area change of the measured profile at time □ from the initial profile at t = 0 s and V_c is positive for erosion. The sand volume V_o per unit alongshore length associated with overwash is obtained by integrating the sand overwash rate q_{bs} from t = 0 s to the time 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. The ratio V_o/V_c indicates the proportion of sand from the pile-protected dune that was overwashed. For nearly the entire duration of the two tests, the ratio V_o/V_c is less than 0.5 indicating that the majority of the sand lost from the dune zone was moved offshore. This offshore-transported sand was deposited in the surf zone area seaward of the initial berm in Figure 6.

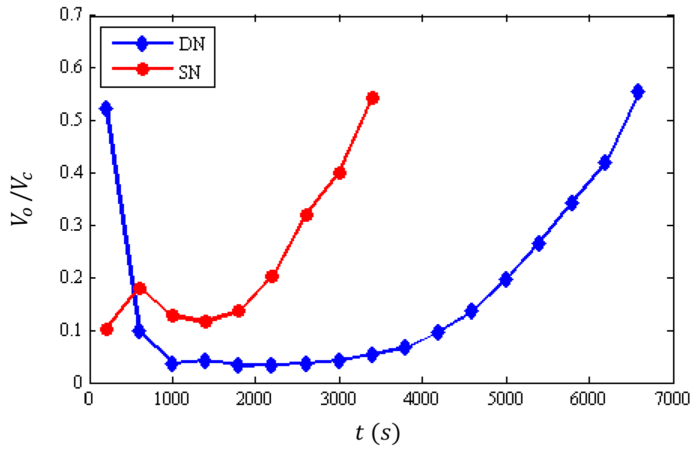

Figure 10. Temporal variations of ratio V_o/V_c during the DN and SN tests.

The dune erosion for the DN and SN tests was caused by both sand overwash over the vertical wall and offshore transport. The reduced porosity decreased the wave overtopping and overwash rates but increased the offshore sand loss. This increased offshore sediment transport resulted in more deposition in the surf zone of x = 15 - 17 m and may have increased wave breaking in the inner surf zone and reduced wave action on the pile fence and dune.

Wide Pile Spacing Tests

Figure 11 shows the measured dune profiles for the DW and SW tests in the zone of x = 15 - 19.9 m of noticeable profile changes in front of the vertical wall. The profiles seaward of x = 15 m did not change significantly. Similar to the narrow pile spacing tests, the dune crest was lowered initially by the seaward sand transport and foreslope scarping and subsequently by wave overtopping and overwash over the vertical wall during both DW and SW tests. Scarping and slumping were also observed. The DW test was terminated at run 7 due to a wave maker malfunction during run 8 where a single large wave significantly changed the bottom profile. The SW test was terminated at run 6 due to excessive alongshore non-uniformity. Comparing the profile evolution of the DW and SW, it can be estimated that the DW test could have endured a minimum of two more runs before termination if the wave maker malfunction had not occurred.

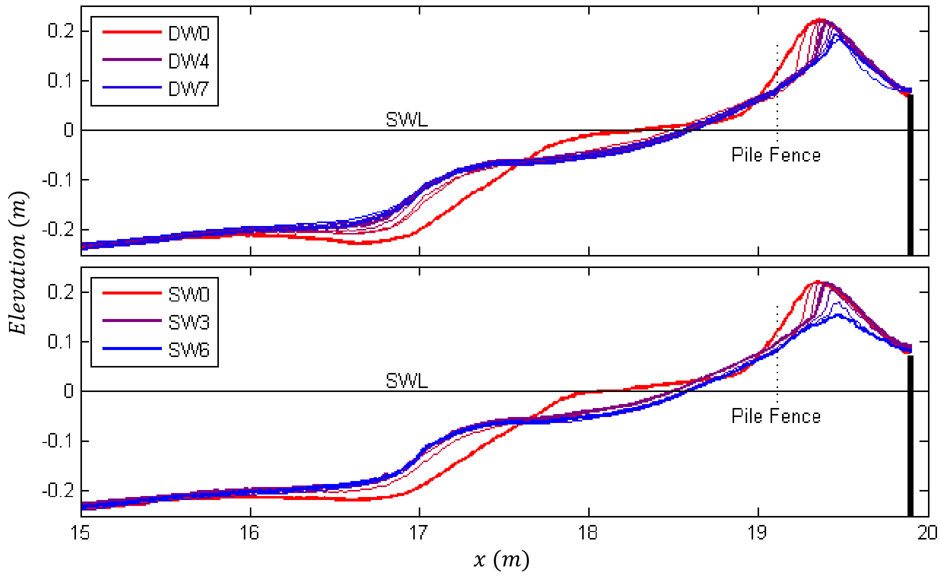

Figure 11. Dune profile evolution for DW (top) and SW (bottom) tests. The color scale from red (initial profile) to blue (final profile) indicates the measured profile number (DW: 0−7; SW: 0−6).

Figure 12 shows the temporal variations of the measured wave (water) overtopping rate q_o and sand overwash rate q_{bs} for the tests. The measured rates of the DW runs increased slowly relative to those of the SW runs. The double rows were effective in reducing q_o and q_{bs}. The smaller porosity of the double row fence reduced wave uprush on the upward slope noticeably.

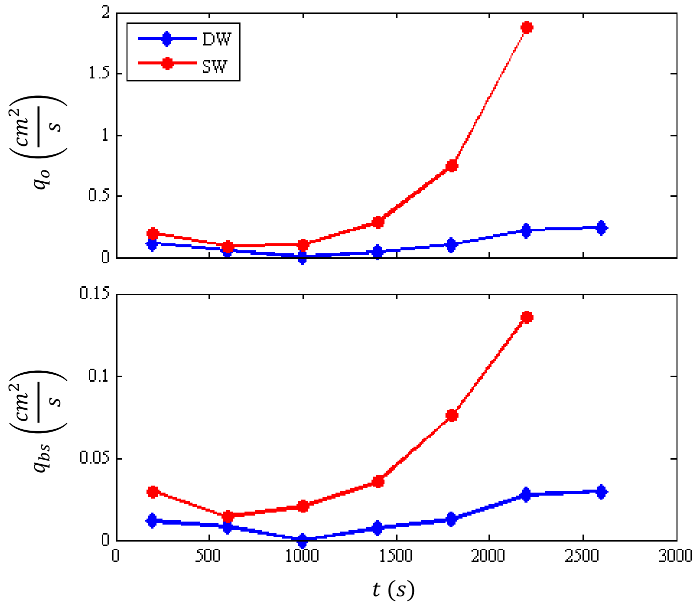

Figure 12. Temporal variations of wave overtopping rate q_o (top) and sand overwash rate q_{bs} (bottom) during the DW and SW tests.

The direction of sediment transport from the zone of *x* = 19.1 – 19.9 m is shown in Figure 13. This zone corresponds to the zone landward of the pile fence aligned alongshore (dune zone). There is a greater proportion of sand moved offshore than overwashed for the entire duration of both the DW and SW tests.

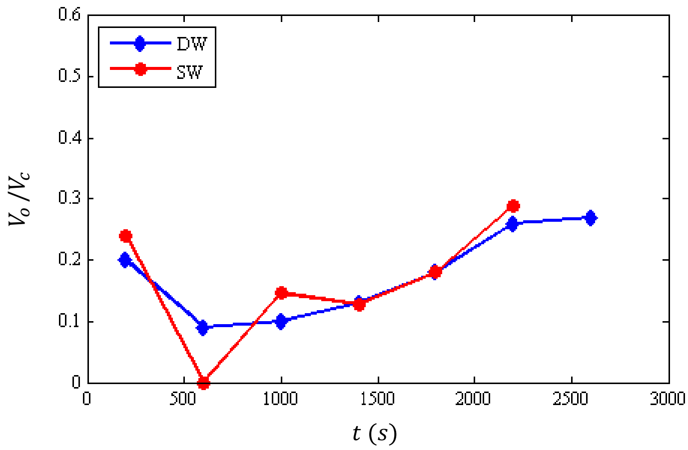

Figure 13. Temporal variations of ratio V_o/V_c during the DW and SW tests.

The dune erosion for the DW and SW tests was caused by some sand overwash over the vertical wall and mostly by offshore transport. The increased offshore sediment transport resulted in more deposition in the surf zone area of *x* = 15 - 17 m in Figure 11 and may have increased wave breaking in the inner surf zone thus reducing wave action on the pile fence and dune.

Pile Toppling Tests

Figure 14 shows the measured dune profiles for the TD and TB tests in the zone of *x* = 15 - 19.9 m of noticeable profile changes in front of the vertical wall. The profiles seaward of *x* = 15 m did not change significantly. The location of the pile fence is indicated by a vertical dotted line with the pile fence located at *x* = 19.12 m for the TD test and *x* = 18.64 m for the TB test. Local pile scouring was observed in the TB test. In both tests, the dune crest was lowered initially by the seaward sand transport and foreslope scarping and subsequently by wave overtopping and overwash over the vertical wall. Scarping and slumping were observed in both tests. The tests were terminated once all the piles had been toppled.

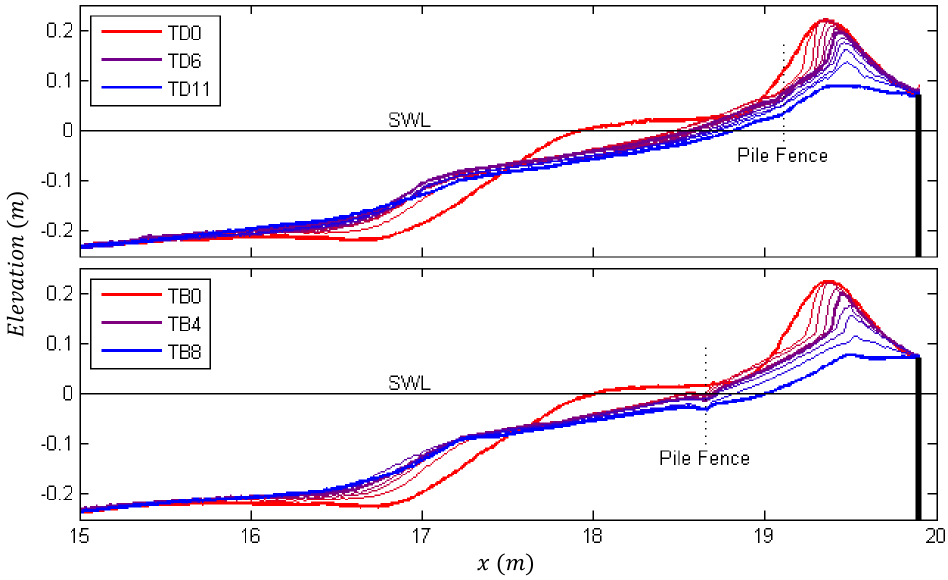

Figure 14. Dune profile evolution for TD (top) and TB (bottom) tests. The color scale from red (initial profile) to blue (final profile) indicates the measured profile number (TD: 0−11; TB: 0−8).

Figure 15 shows the average porosity of the pile fence in the TD and TB tests increasing with time where the average porosity is calculated by assigning the porosity of 1.0 to toppled piles and the initial porosity of 0.55 to non-toppled piles. The number of piles placed alongshore was 58 at the beginning of the TD and TB tests. The initial porosity of 0.55 increased to 1.0 with the increase of the number of toppled dowels. The average pile burial depth at failure during the TD and TB tests were 2.2 cm and 5.7 cm, respectively. The probability of pile burial depths at failure is shown in Figure 16. The burial depth of the toppled piles was based on the beach profile measured at the beginning of the toppling run.

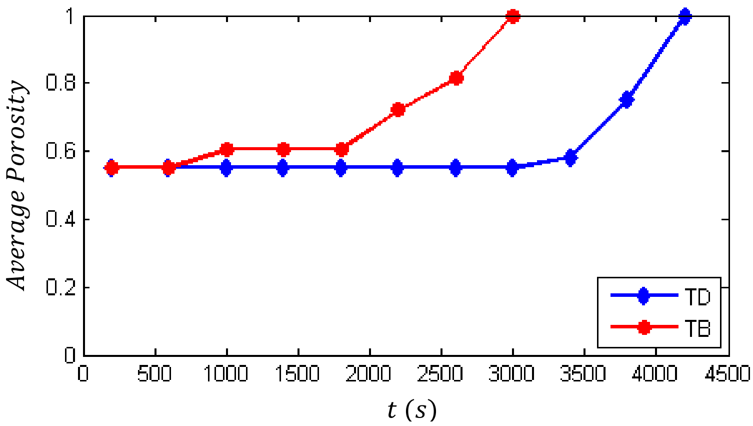

Figure 15. Temporal change in average porosity for the TD and TB tests.

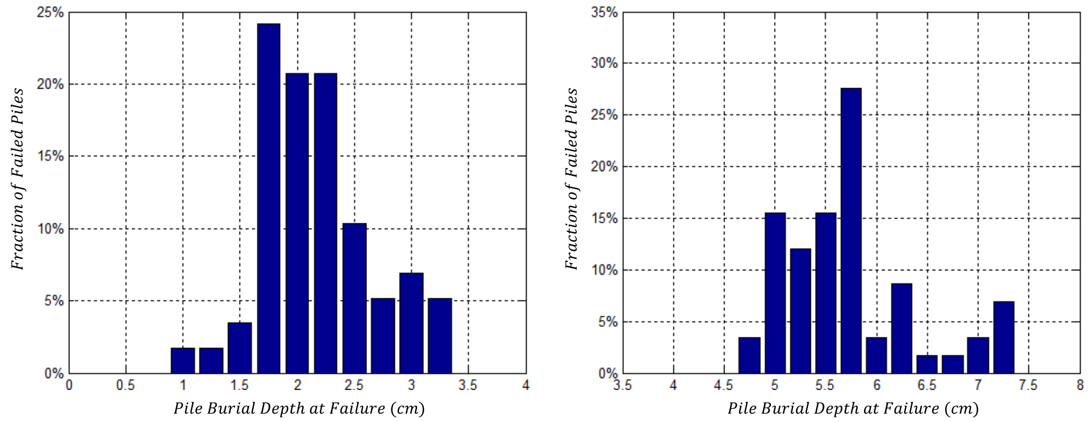

Figure 16. Pile burial depth at failure for the TD (left) and TB (right) test.

Figure 17 shows the temporal variations of the measured wave (water) overtopping rate q_o and sand overwash rate q_{bs} for the tests. Increases in wave overtopping and sand overwash corresponds to an increase in average porosity due to pile toppling which leaves the dune less protected. The piles of the TB test toppled earlier than those of the TD test due to the larger water depth on the berm and submergence of the pile fence in the TB test. Wave action on the pile fence on the berm in the TB test was stronger, causing toppling to occur with larger pile burial depth.

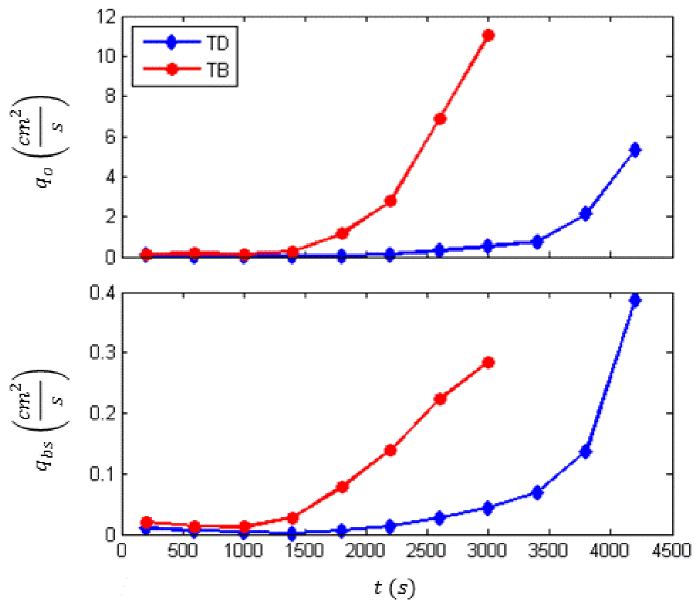

Figure 17. Temporal variations of wave overtopping rate q_o (top) and sand overwash rate q_{bs} (bottom) during the TD and TB tests.

The piles of the TB test, located at the berm, experienced more wave action and were toppled at a larger pile burial depth. The TD test also had lower wave overtopping and overwash rates compared to the TB test. Therefore, the pile fence was recommended to be installed near the toe of the dune foreslope.

Effect of Porosity

Figure 18 shows a comparison among the four "no toppling" tests. As porosity decreased, the onset of major overtopping and overwash was delayed and the dune became more resilient. Tests SN and DW, which have the same porosity but have difference in pile fence configurations, have similar results. This indicated the validity of the porosity definition for the double rows. In the absence of pile toppling, porosity was the most significant factor in determining the performance of the pile fence located near the dune toe.

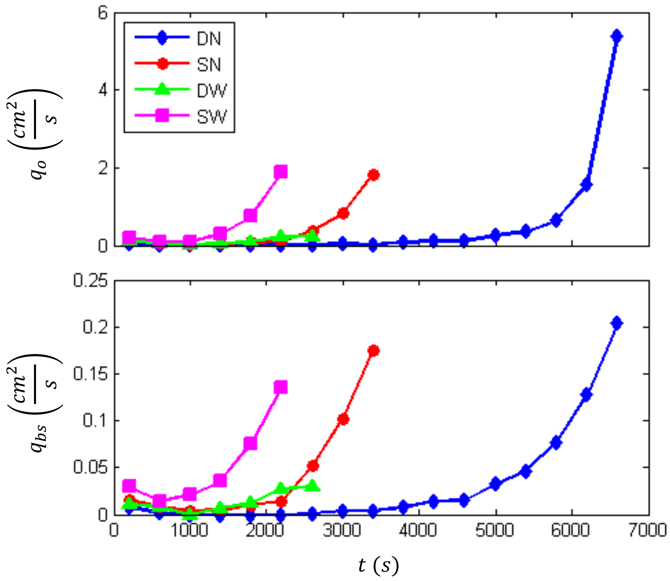

Figure 18. Temporal variations of wave overtopping rate q_o (top) and sand overwash rate q_{bs} (bottom) for the DN, SN, DW and SW tests.

Comparison with Bare Dune

Gralher et al. (2012) conducted a test on the same dune profile used in this experiment without a pile fence. Their test, called the HB (high bare dune) test, was terminated after run 6 wherein the dune crest elevation reached that of the impermeable vertical wall. The HB test is compared with the SW test, which was also terminated after run 6. Although the pile fence in the SW test did not significantly increase the resiliency of the dune, it reduced the amount of wave overtopping and overwash in comparison to the HB test. Figure 19 indicates that a porosity of 0.78 may be too high to provide sufficient resiliency to the dune. Therefore, a porosity of about 0.5, similar to that of the SN and DW tests, was recommended to obtain significant wave overtopping and overwash reduction. This required porosity is consistent with the Coastal Engineering Manual (CEM) recommendation of porosity of about 0.5 for wind fences. Figure 20 shows that the fence increased the proportion of sand transported offshore, which provides the possibility for the sand to return to the foreshore over time. The sand remaining on the foreshore caused wave breaking and protects the dune.

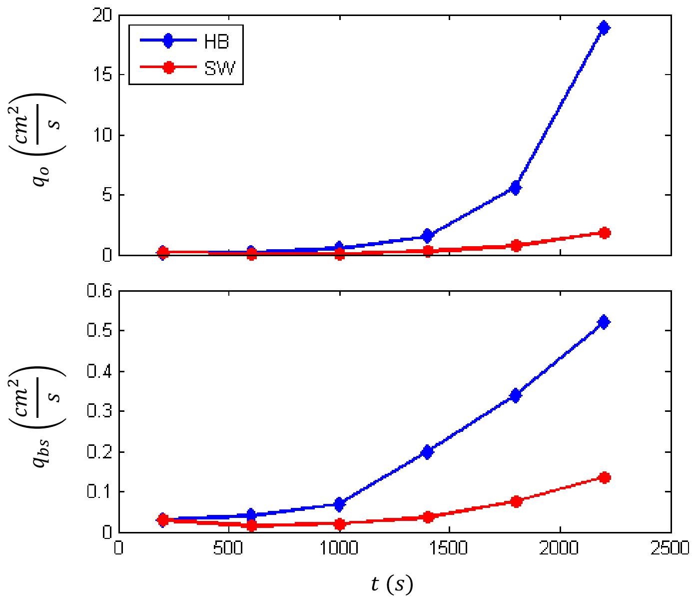

Figure 19. Temporal variations of wave overtopping rate q_o (top) and sand overwash rate q_{bs} (bottom) during the HB and SW tests.

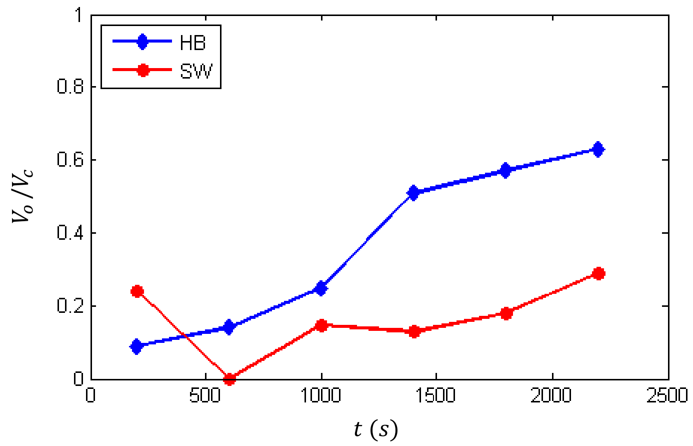

Figure 20. Temporal variations of V_o/V_c during the HB and SW tests.

CONCLUSIONS

The purpose of this study was to determine the possibility of using pile fences to reduce the overtopping and overwash of dunes to enhance their resiliency. A total of six laboratory tests were conducted. Four tests were used to analyze the influence of pile fence porosity with no pile toppling. Two tests were used to examine the effect of fence location and pile toppling. Eight capacitance wave gauges and three velocimeters recorded hydrodynamic data throughout the experiment. High resolution bathymetry of the profile was measured by the laser line scanner. The collection basin and the sediment trap, in which water and sediment transported over the vertical wall was collected, allowed for the measurement of wave overtopping and sediment overwash rates for each run.

The four "no toppling" tests were conducted with the centerline of the fence located at the same cross-shore location on the dune foreslope. The burial depth of the piles was adjusted after each run to maintain a constant depth to prohibit pile toppling. It was observed that lower porosity fences were able to better enhance dune resiliency with the DN (double row, narrowly spaced) test performing the best (ε = 0.10). The SN (single row, narrowly spaced) and DW (double row, widely spaced) tests had different configurations but the same porosity (ε = 0.55) based on the porosity definition of Equation 1. It was observed that these fences performed very similarly indicating the validity of characterizing the pile fence by the proposed porosity. The SW (single row, widely spaced) test (ε = 0.78) did not enhance the resiliency of the dune as it was only able to withstand the same number of runs of that of a bare dune (ε = 1.0). Therefore, it was recommended that a porosity of about 0.5 or less be used to obtain significant enhancement in dune resiliency. This porosity also corresponds to the porosity recommended by the CEM for the design of wind fences.

In the tests that allowed for pile toppling, the same pile fence configuration was used (single row, narrowly spaced, ε = 0.55) but the fence was located on the dune foreslope for the TD (toppling, dune) and on the berm in the TB test (toppling, berm). Burial depths for the piles were allowed to vary and toppling of the piles was recorded during each run. While more erosion was experienced by the piles in the TD test, the strong wave action encountered by the piles in the TB test caused the pile toppling earlier. Therefore, it was recommended that the pile fence be located on the foreslope of the dune.

It was observed that the presence of the pile fence increased the proportion of offshore sediment transport from the pile-protected dune zone. Without any dune protection, the majority of the sand lost from the dune was overwashed after the third run, whereas in the tests conducted in this study, the majority of the sand was lost offshore for nearly the entire duration of all the tests. The offshore transported sand was deposited in the surf zone, leading to additional wave breaking.

The results of this study showed that pile fences may be promising to enhance dune resiliency. However, this study was limited to the specific diameter, heights, spacing, alignment, location and burial depth of cylindrical wooden dowels in the small-scale laboratory tests. The results of this study will be replicated in the numerical model CSHORE. CSHORE has been shown to predict the profile evolution and wave overtopping and overwash rates of small-scale and prototype bare dunes and vegetated dunes (Figlus et al. 2011; Ayat and Kobayashi 2014). The pile fence effects have been incorporated in CSHORE as the drag force acting on the wooden dowels. The verified CSHORE may be used for field applications.

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