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DUNE EROSION TESTS TO STUDY THE INFLUENCE OF WAVE PERIODS

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The aim of the study was to quantify the effects of the wave period on dune erosion. Attention was focussed on 2D cross-shore effects in a situation with sandy dunes and extreme wave conditions. Large-scale physical model tests were set up to provide the necessary data for the study on a scale as close to prototype as possible. It was concluded that a longer wave period leads to a larger dune erosion volume and to a larger landward retreat of the dune face.

1 INTRODUCTION

Dunes in The Netherlands act as primary sea defence for the lowlands behind them. Since this is a densely populated area, it is important to assess their safety against flooding. Therefore, the strength of the dunes needs to be predicted under the hydraulic loads in a normative storm surge. In The Netherlands the normative conditions refer to rather small chances of failure (≈ 10^{-4} to 10^{-5} per year). The strength of the dunes can be determined by predicting the volume of dune erosion during an extreme storm, see Fig.1. Failure of the dunes takes place when the rate of dune erosion is so large that flooding of the lowlands behind the dunes occurs. Wave periods during extreme storm conditions along the Dutch coast could be longer than previously assumed. Although the results of small-scale physical model tests (Coeveld *et al.*, 2005) revealed that a longer wave period could lead to more dune erosion, these effects were never verified and quantified in a near-prototype situation.

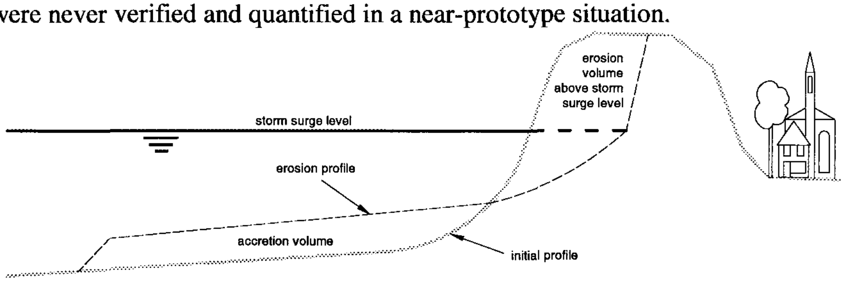

Figure 1. Initial cross-shore profile and erosion profile after an extreme storm event.

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The objective of the study was to obtain information on the effects of the wave period on dune erosion, as input for new guidelines for the Dutch legislator for the assessment of dune safety. Several large-scale dune erosion tests were performed in which the wave attack was simulated on a coastal cross-shore sandy profile that is considered as characteristic for the situation at the Dutch coast (hereafter: 'reference profile'). Storms with equal duration, water depth and deep-water wave height, but with different wave periods were used for that purpose. Next to the investigation of effects of the wave period on dune erosion, it was investigated which wave period should be used for a proper characterization of the influence of wave spectra on dune erosion.

2 DESCRIPTION OF PHYSICAL MODEL

The physical model was set up in the Delta flume of Delft Hydraulics. This flume has an effective length, width and height of 225 m, 5 m and 7 m respectively. The wave generator is equipped with Active Reflection Compensation to prevent reflected waves to re-reflect into the flume, and 2nd order wave steering. Irregular waves with a wave height up to 1.9 m can be generated depending on the water depth and the wave period.

2.1.1 Characteristic cross-shore bed profile

The characteristic cross-shore bed profile that was used for the tests is given in Fig.2. This strongly schematized profile contains one dune. No banks or channels are present in the foreshore. To translate the prototype situation to a model that fits in the flume, use was made of the scaling relations derived by Vellinga (1986).

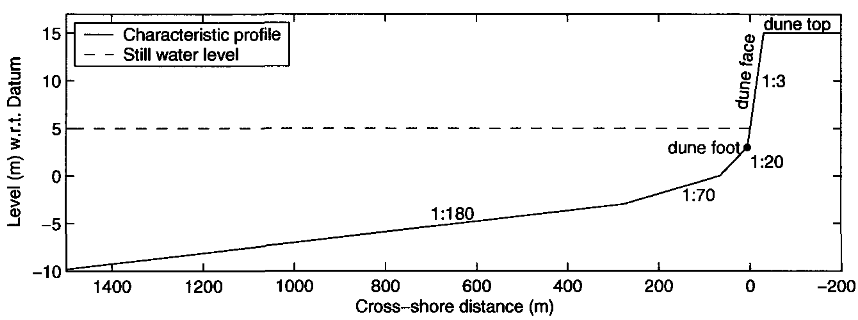

Figure 2. Characteristic cross-shore bed profile on which the bed profile in the tests was based.

2.1.2 Scale relations

Interpretation of results of small- and large-scale physical model tests in relation to prototype situations requires scale relations. For dune erosion during extreme storm conditions, deriving such relations is not very straightforward. Theoretical elaborations alone are insufficient to come up with a consistent set of scale relations, because the applied theories have a limited validity (*e.g.* linear wave theory is less reliable within the surf zone and important physical processes in dune erosion are not fully understood). In the past, the results of an extensive series of small- and large-scale physical model tests were analyzed (see *e.g.* Vellinga, 1986), which resulted in a more robust set of scale relations for dune erosion. Although indications exist (see Delft Hydraulics, 1996) that the scale relations could be improved, no reliable updates of the scale relations can be made without additional experimental data. Ultimately, these scale relations were used to translate a prototype situation to a model that fits in the flume. For a certain depth scale factor (n_d) and fall velocity scale factor (n_w) the desired profile steepness factor of the initial profile can be determined with:

$$S_1 = \frac{n_l}{n_d} = \left(\frac{n_d}{n_w^2}\right)^{0.28} \tag{1}$$

where n_l (-) is the horizontal length scale factor. Ideally an undistorted profile is applied in the model, but since proper modeling of n_w in relation to n_d is difficult, one often ends with a value for the steepness factor of $S_1 > 1$. However, the dimensions of the flume often require an even steeper profile, multiplied with a factor S_0 instead of the desired factor S_1. Taking this profile steepness factor into account the dune erosion of an initial profile is thought to be properly simulated at a smaller scale in a wave flume. The erosion area (or volume per linear meter) scale factor is:

$$n_A = n_l \cdot n_d = n_d^2 \cdot \left(\frac{n_d}{n_w^2}\right)^{0.28} \tag{2}$$

By multiplying the measured dune erosion volume (per linear meter) with n_A the prototype volume is obtained which applies for a prototype initial profile that is a factor $S = S_0 / S_1$ steeper than the reference profile. S_0 is the steepness factor that was applied to the profile in the model.

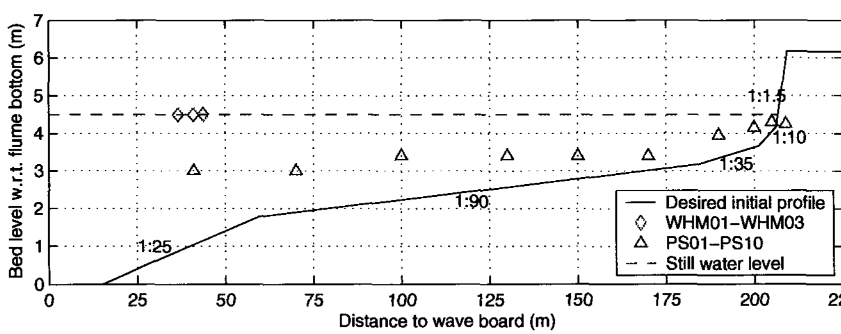

Figure 3. Initial profile in flume and instrument positions (WHM = wave height meter, PS = pressure sensor).

2.1.3 Set up of physical model

The scale at which the model was set up, was aimed to be as close to prototype as possible to minimize scale effects. A depth scale factor of $n_d = 6$ and a profile steepness factor of $S_0 = 2$ resulted in wave conditions that could be generated by the wave generator and to a profile that fitted in the flume, see Fig.3. At a water depth of 2.7 m (~ 2 H_{m0}) the foreshore was cut off with a 1:25 slope. The diameter of the applied sediment was $D_{50} = 200$ μm. This diameter is slightly smaller than the desired diameter, which resulted in a value of the factor S that was about 3 to 4% too large.

2.2 Test programme

Table 1 shows the test programme with the hydraulic conditions at the wave board. Tests T01, T02 and T03 were set up to provide insight in the effects of the wave period; the wave period is the only parameter that varied in these tests. The wave conditions in Tests T01, T02 and T03 correspond to peak wave periods in a prototype situation of $T_p = 12$ s, $T_p = 15$ s and $T_p = 18$ s respectively, and to a prototype wave height of $H_s = 9$ m. Tests T01 and T03 were performed twice which provides insight into the reproducibility of the tests. A Pierson-Moskowitz wave spectrum was applied in Tests T01 to T03. Tests DP01 and DP02 were carried out with double-peaked wave spectra to gain insight into the optimal measure to characterize the influence of wave spectra on dune erosion, see Fig.4. In addition to these 7 tests, an 8th test was carried out with a different initial cross-shore profile. This test is not described in this paper.

Table 1. Test programme with hydraulic conditions at the wave board.

Test	H_{m0} (m)	T_p (s)	$T_{m-1,0}$ (s)	s_p (-)	$s_{m-1,0}$ (-)
T01	1.5	4.90	4.45	0.040	0.049
T02	1.5	6.12	5.56	0.026	0.031
T03	1.5	7.35	6.68	0.018	0.022
DP01	1.5	6.12	3.91	0.026	0.063
DP02	1.5	7.35	5.61	0.018	0.031

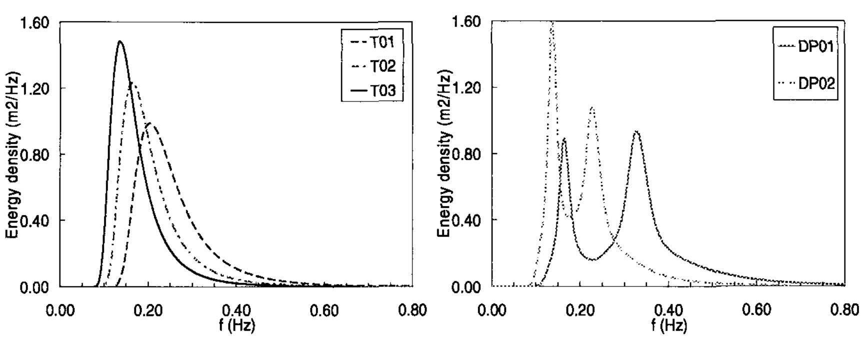

Figure 4. Applied wave energy spectra.

All tests were carried out with a fixed water depth of 4.5 m in the flume near the wave board. The total duration of each test was 6 hours. With a time scale factor of $n_t = \sqrt{n_d} = 2.4$ a test duration of 6 hours corresponds with a prototype storm duration of almost 15 hours which was considered sufficiently long to study dune erosion during extreme storm events. For example, for the Dutch practice of verifying the safety level of the dunes a normative storm event is characterized with a fixed water level and prototype storm duration of 5 hours. The tests were temporarily interrupted to carry out bed profile measurements at the following fixed time intervals:

A. 0 till 6 minutes or 0 till 0.1 hour;
B. 6 till 18 minutes or 0.1 till 0.3 hour;
C. 18 till 60 minutes or 0.3 till 1.0 hour;
D. 60 till 122 minutes or 1.0 till 2.04 hours;
E. 122 till 240 minutes or 2.04 till 6.0 hours.

The time intervals in the beginning of a test are the shortest, because in the beginning of a test the erosion rates are the highest. Similar time intervals were used in earlier research (*e.g.* Delft Hydraulics, 1984).

2.3 Measurements

Bed profile measurements were carried out with a so-called mechanical (amphibious) bed profile follower. The profile follower had a wheel with a diameter of 0.1 m and a width of 0.05 m, which is sufficiently accurate to follow bed ripples. The measurements were carried out before and after each test and after each temporary test interruption in three cross-shore transects; one along the longitudinal flume axis and the other two at 1.25 m on both sides of the flume axis. The figures of bed profile measurements presented in this paper concern the average of the three cross-shore transects. The average of the profile measurements obviously does not give reliable information on profile features that vary strongly in cross-flume direction (*e.g.* bed ripples).

Besides, wave conditions were obtained from three resistance-type wave height meters (WHM in Fig.3) and from pressure sensors installed at ten locations along the profile (PS in Fig.3). Especially, the pressure measurements provide valuable information on the wave transformation along the profile. Furthermore, particle size distributions of several bed samples were determined and also fall velocities of the sediment.

The physical processes underlying dune erosion need to be further investigated to explain the effects of the wave period (see *e.g.* Van Thiel de Vries *et al.*, 2006). Therefore, additional measurements of flow velocities and sediment concentrations were carried out with several types of instruments. Furthermore, four cameras were installed to obtain stereo video measurements from which -amongst others- information on profile development can be deduced (see for some fundamentals of the applied technique Holland *et al.*, 1997).

3 TEST RESULTS

3.1 Wave propagation over the foreshore

The wave propagation over the foreshore was measured using the wave gauges and pressure transducers. Fig.5 shows the wave heights (including reflected waves) obtained from the pressure measurements in Tests T01, T02 and T03 (with single-peaked wave spectra) during time interval E (from 2 till 6 hours). Differences in wave height exist, but they are relatively small. Wave spectra from the water surface elevations obtained from the pressure sensors (in time interval E) showed that the wave energy dissipates along the profile and shifts towards lower frequencies for all tests, see Fig.6. Close to the dune (at 200 m), most of the energy is present in low frequencies.

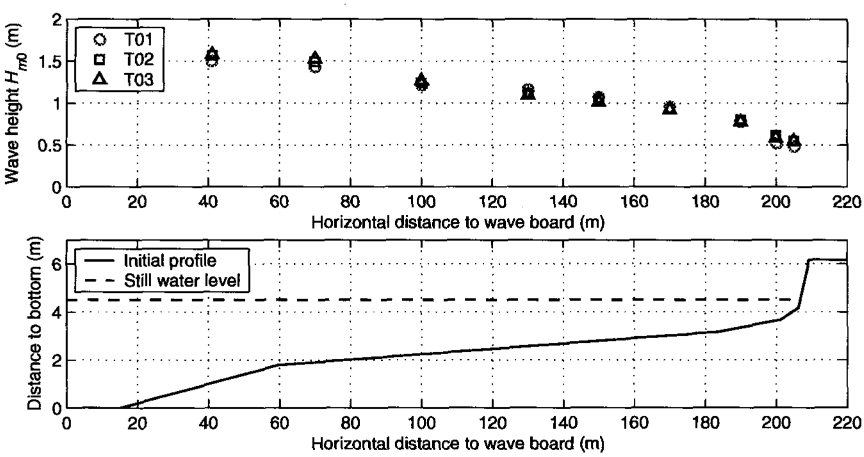

Figure 5. Wave heights obtained from measurements with pressure sensors.

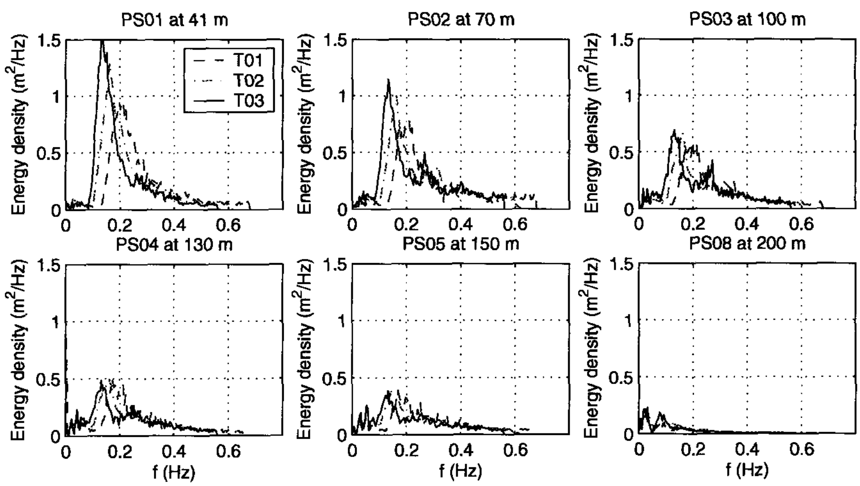

Figure 6. Wave spectra obtained from pressure sensors PS01 – PS05 and PS08.

3.2 Visual observations on dune erosion process

The erosion of the dune face showed some variation in cross-flume direction, but these irregularities generally disappeared after the first hour, see Fig.7.b. It seems therefore legitimate to use an average of the bed profile measurements of the three transects for the purpose of dune erosion analyses.

The erosion started at the toe of the dune face where the slope became steeper until it was nearly vertical, or even slightly negative (overhanging). This transition between the beach and the dune face gradually moved in landward direction and therewith the level of this start increased. During the wave attack at the dune big lumps of sediment fell or slid down the dune face on the beach in front of the dune. The dimensions of these lumps varied, but the length in cross-flume direction was mostly smaller than the entire width of the flume, but often exceeded one third of the flume width. In the along-flume direction, the length was about 0.1 to 0.3 m. Once these lumps had fallen down on the beach, the sediment was transported away from the dune face. These lumps of sediment sometimes temporarily obstructed further dune erosion by direct wave attack. The part of the dune face that was still entirely exposed to waves was at that moment more susceptible for erosion than the obstructed part. This process seemed to reduce the variations of the erosion profile in cross-flume direction. The size of the lumps of sediment did not seem to vary much in time: at the beginning of the tests (after 1 hour) the size was roughly the same as at the end of the tests. The period of time it took before a lump of sediment was removed from the beach seemed to be shorter at the beginning of the tests than at the end of the tests.

The moment that a lump of sediment fell down did not always coincide with the moment of a (large) wave impact. Differences in the dune erosion process were not observed visually for different wave periods.

After the tests, the water was pumped out of the flume and the bed surface was inspected. The surface of the profile generally was very smooth and no significant bed ripples were observed.

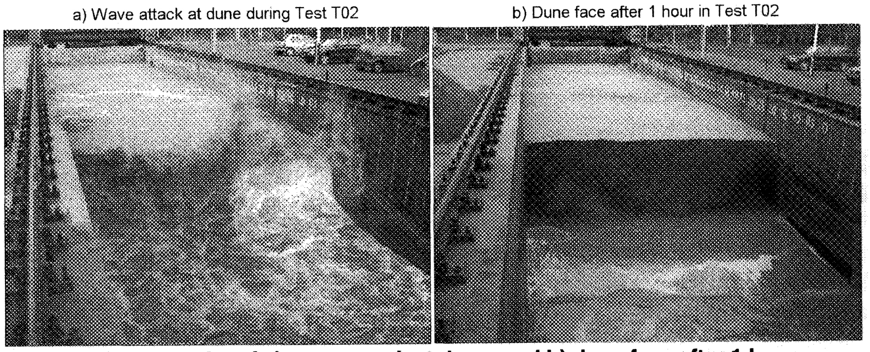

Figure 7. Photographs of a) wave attack at dune, and b) dune face after 1 hour.

3.3 Measured bed profiles

The bed profile only shows considerable changes in a relatively small part of the entire profile in the flume between about 170 m and 220 m from the wave board. The rest of the profile does hardly change during the tests, see Fig.8.a. Fig.8 and Fig.9 show the time-development of the measured cross-shore bed profiles for Tests T01 and T03 respectively. Since the time intervals increase per measured profile (see Section 2.2), it can be seen that the retreat of the dune face is clearly non-linear in time.

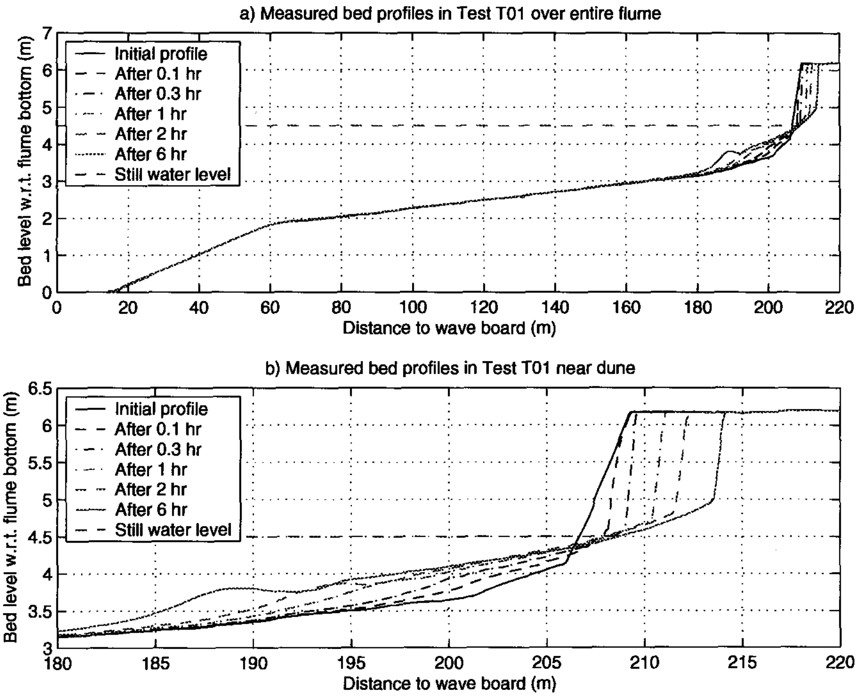

Figure 8. Measured bed profiles in Test T01 a) over entire flume, and b) near dune.

Fig.10 compares the bed profile measurements after 6 hours for Tests T01, T02 and T03. It shows that the retreat of the dune face is largest in Test T03 (with the longest wave period) and smallest in Test T01 (with the shortest wave period). The differences in the shape of the bed profile for different wave periods are small, but the change in dune foot location, slope of the profile and the shape of the deposit area for increasing wave periods is very consistent. The dune foot is located at the intersection of the relatively steep dune face and the beach just in front the dune face. The horizontal position of the dune foot moves more landward for the longest wave periods, while the vertical position hardly varies between the conditions with different wave periods. The slope of the profiles around the still water level is a bit steeper for the short wave periods.

After 6 hours the seaward edge of the deposit area is located about 1.2 m further seaward in Test T03 compared to Test T01.

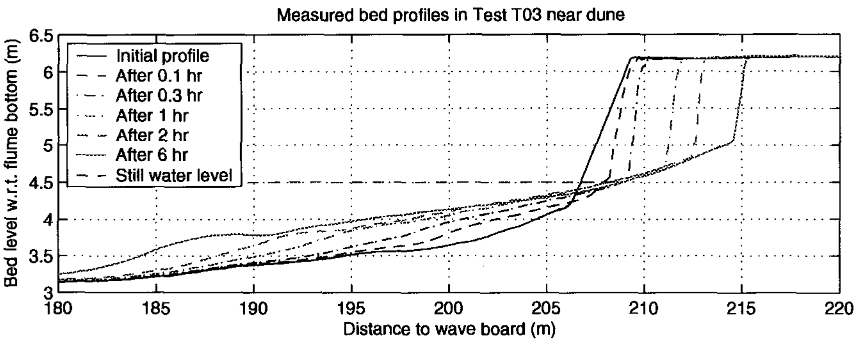

Figure 9. Measured bed profiles in Test T03 near dune.

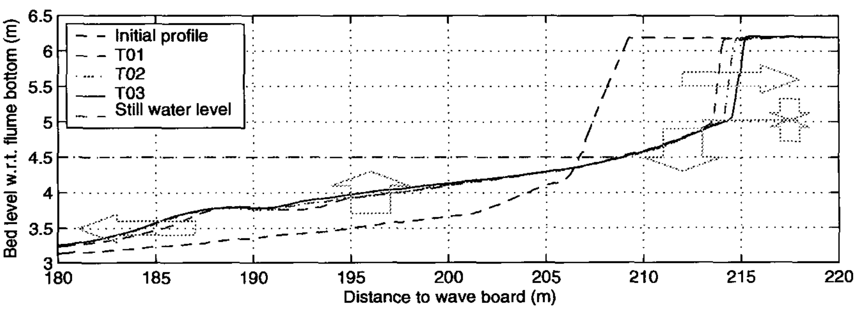

Figure 10. Comparison of measured bed profiles in tests with different wave periods.

3.4 Erosion volumes

Fig.11.a shows the development of the dune erosion volumes above the still water level (or storm surge level) in all tests. The dune erosion volume after a certain period of time is based on the difference between the initial profile and the measured profile after that period of time. In the beginning of the tests the erosion volumes increase very fast compared to the increase towards the end of the tests. More and higher waves can attack the dune face at the start of the tests, because the water depth in front of the dune face is then larger than at the end of the tests. Tests T01 and T03 have each been repeated. Repetition of the tests led to differences of less than 2.5% in the total eroded volumes after 1, 2 and 6 hours. The differences after 0.1 and 0.3 hour were slightly larger. This indicates that the reproducibility of the results of the tests is good. Hereafter, for T01 and T03 the average of the two test results with equal wave conditions have been used.

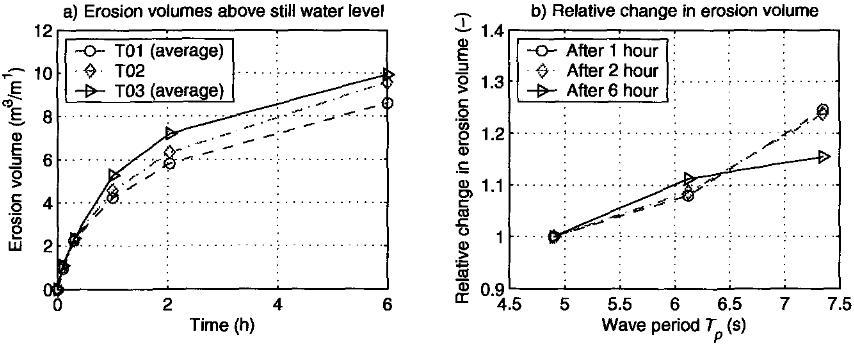

Figure 11. a) Erosion volumes above still water level in Tests T01, T02 and T03, and b) relative change in erosion volume in Tests T02 and T03 compared to Test T01.

Fig.11.b shows the relative change in dune erosion volume of Tests T02 and T03 compared to Test T01. The increase in volume between the shortest and the mid-wave period varies about 8% to 11%, depending on the stage in the tests. The increase in volume between the shortest and the longest wave period varies from about 15% to 25%, depending on the stage in the tests. This is somewhat smaller than the increase of 25% to 35% that was observed in the small-scale tests (see Coeveld *et al.*, 2005) for an increase in wave period of about 50%. This difference can probably be attributed to the differences in scales (large-scale tests: n_d = 6, small-scale tests: n_d = 30 and 40). Since the large-scale tests are closer to the prototype situation than the small-scale tests, the (qualitative) results of the large-scale tests are generally considered to be more reliable.

Because dune erosion occurs by lumps of sediment falling down the dune face (as described in Section 3.2), the development of dune erosion is a bit discontinuous in time. Thus, for a certain period of time the dune erosion volume remains more or less the same until a lump of sediment falls down the dune face. This lump is removed from the beach by the following waves increasing the dune erosion volume. The effects of this discontinuity on the relative change in dune erosion volume in time are larger at the beginning of a test than towards the end of a test. Therefore, the dune erosion volumes after 1 hour, 2 hours and 6 hours test duration provide a better basis to determine the effects of the wave period on the dune erosion volume than the erosion volumes after 0.1 hour and 0.3 hour test duration. The increase in dune erosion volume between the shortest wave period and the longest wave period (*i.e.* an increase of 50%) was found to be 25%, 24% and 15% after 1 hour, 2 hours and 6 hours test duration respectively.

3.5 Influence of a characteristic wave period

For several coastal processes (wave run-up, wave overtopping and the stability of rock slopes) it appeared that the wave period $T_{m\text{-}1,0}$ (see *e.g.* Van Gent, 2001) can be used to characterize the influence of non-standard wave energy spectra on these processes; the peak wave period T_p is not a suitable parameter for non-standard wave energy spectra. Using the results from the tests with double peaked spectra, it can be analyzed whether this is also valid for dune erosion.

Fig.12 shows the erosion volumes obtained from Tests T01, T02 and T03 (with single-peaked wave spectra) and Tests DP01 and DP02 (with double-peaked spectra) versus respectively the peak wave period T_p at the wave board and the spectral wave period $T_{m\text{-}1,0}$. Fig.12.a shows the erosion volumes versus the peak wave period. This figure clearly shows that using the peak wave period leads to results that are not on the same trendline; the volumes in Tests DP01 and DP02 do not show the same dependency on the peak wave period as the volumes in the tests with the single-peaked spectra. Fig.12.b shows that the spectral wave period provides a more consistent dependency; the results are on the same trendline. This indicates that the spectral wave period $T_{m\text{-}1,0}$ can better be used to characterize the influence of wave energy spectra on dune erosion, while the peak wave period cannot be used for spectra that deviate from standard single-peaked spectra.

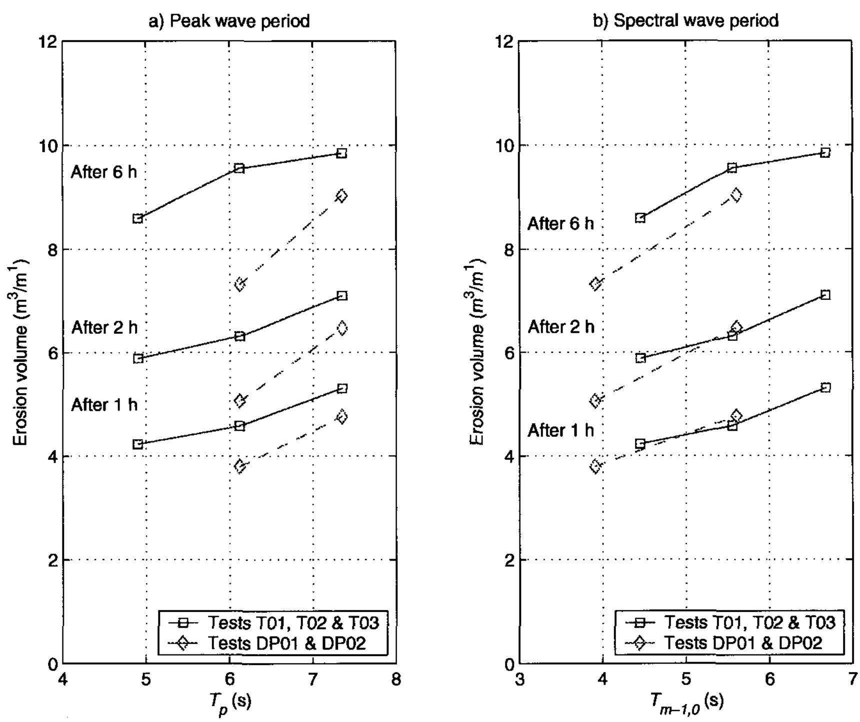

Figure 12. Erosion volumes above still water level after 1, 2 and 6 hours as a function of left: peak wave period T_p, and right: spectral wave period $T_{m\text{-}1,0}$.

3.4 Other measurements

Samples of the sediment at the bed were taken at 180 m, 190 m, 200 m, 210 m and 220 m from the wave board before each test, after 2 hours and after 6 hours in Tests T01, T02 and T03. The mean and the standard deviation of the grain size D_{50} are 200 μm and 15 μm respectively, and the means of the grain sizes D_{10} and D_{90} are 142 μm and 286 μm respectively.

The average water temperature varied during the tests between 5.0 °C in Test DP02 and 9.7 °C in Test T02.

The fall velocity of the sediment is measured with sub samples of the bed samples used for the determination of the particle size distribution. The water temperature in the settling velocity tests is measured, because it affects the velocity. Use is made of the VAT-method ('Visual Accumulation Tube') described in Van Rijn (1993). The fall velocities were estimated at $w = w_{50}$ = 0.023 m/s for Tests T01, T02 and DP02, and w_{50} = 0.022 m/s for all other tests, corresponding with the average grain size of $D = D_{50}$ = 200 μm.

4 CONCLUSIONS

The objective of this study was to investigate the effects of the wave period on dune erosion. The emphasis in the investigation was put on the verification and quantification of the effects of the wave period on the dune erosion volume. Large-scale physical model tests were carried out to simulate dune erosion under extreme storm conditions at a near-prototype scale. Based on the results of the tests, the following effects of the wave period on dune erosion could be found:

- Dune erosion volumes increase for increasing wave periods. For an increase of 50% in the wave period, the dune erosion increased with 25%, 24% and 15% after 1 hour, 2 hours and 6 hours test duration respectively.
- The dune face retreat increases for increasing wave period.
- The slope of the cross-shore bed profile around the still water level becomes gentler for increasing wave period.
- The spectral wave period $T_{m-1,0}$ is a better measure to characterize the influence of wave energy spectra on dune erosion than the peak wave period T_p.

The physical processes underlying dune erosion need to be further investigated to explain the effects of the wave period. The additional measurements of flow velocities and sediment concentrations that were carried out for this purpose, need to be further analyzed.

It should be noted that the above mentioned effects of the wave period on dune erosion might be differently for other initial profiles, wave heights, or sediment characteristics.

The test results provide valuable information to obtain improved prediction methods for dune erosion, see for instance Van Gent *et al.* (2007).

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