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AVALANCHING OF THE DUNE FACE: FIELD OBSERVATIONS AND EQUILIBRIUM THEORY

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Abstract: A field experiment to study dune erosion was conducted on the Sand Engine near Kijkduin, the Netherlands, from November 7th 2021 to January 7th 2022. Two artificial unvegetated dunes were constructed near the high water line, and experienced significant erosion through avalanching during three storms. This paper aims to identify what drives dune erosion through avalanching by using the collected data and equilibrium theory. Results suggest that the cumulative volume eroded through avalanching during a single high water is positively correlated with the profile mismatch between the pre-storm profile and a 'storm equilibrium profile', described by a 2/3rd power law, an empirical coefficient *A*, and the total water level. This mismatch is quantified by calculating the area integral of the profile that is acquired when the upper 35 m of the pre-storm profile is subtracted from the upper 35 m of the equilibrium profile. Avalanching commences when this mismatch becomes larger than approximately 0, after which 1 m^3/m of sediment erodes from the dune face for every 3 m^3/m mismatch. In addition, during one event avalanching occurred even though the elevation of the total water level did not exceed the initial elevation of the dune toe. This implies that a total water level that exceeds the initial elevation of the dune toe is not a requisite for avalanching and a collision regime to occur, which contradicts conventional definitions of dune erosion regimes.

Introduction

Storm conditions can lead to excessive dune erosion with potential floods as a consequence, especially for sandy coastlines protected by dunes. To assess the risks these areas face, engineers often rely on dune erosion models to predict storm impact. These models are based on knowledge of underlying hydrodynamic and morphodynamic processes.

Field observations during storms can provide useful information and further expand knowledge and modelling techniques. Using field observations, a coastal stretch can be studied under natural and real-life conditions. However, field observations during storms are difficult to perform because (1) storms can be dangerous for observers in the field, (2) storms are unpredictable and do not occur frequently, and (3) hydrodynamic conditions cannot be controlled; Ideal conditions to study a specific process do not necessarily occur. A solution to these issues can be found in manipulative field experiments. In manipulative field experiments, a setup can be built or altered in the field in such a way that a process of interest (e.g. dune erosion) is forced or very likely to occur (e.g. under already moderate and therefore more frequent events).

A manipulative field experiment to study dune erosion was conducted near Kijkduin, the Netherlands, from November 2021 to January 2022. Two artificial unvegetated dunes were constructed near the high water line, and experienced substantial erosion through avalanching during three storms. This paper aims to identify what drives dune erosion through avalanching, using the collected data and equilibrium theory.

In the first section the field observations are described. In the second section, equilibrium theory is introduced, and a formulation of the post-storm equilibrium profile is derived based on the second storm. The third section presents a method using the equilibrium profile to predict whether avalanching will occur and if so with what magnitude. The final section discusses findings and draws conclusions with regards to avalanching of the dune face.

Field Observations

Field Site

The field site consisted of two prototype, unvegetated dunes of 5.5 m high and 150 m long, which were built just above the high waterline (Figure 1). Due to a different coastline orientation and nearshore bathymetry, these dunes were expected to erode differently during storm conditions.

A total of three storms occurred during the field experiment: one in November, one in December, and one in January (Figure 1). Dune 1 suffered significant erosion through avalanching and remained in the collision regime during all three storms. Dune 2 also experienced avalanching and remained in the collision regime during the November and December storm, but experienced overwash during the January storm and was eventually destroyed by January 6th.

Fig. 1 Aerial photograph of the field site including offshore hydrodynamic conditions during the three campaign storms. The water levels were measured at the Hoek van Holland and Scheveningen stations. The wave conditions were measured at the offshore EuroPlatform station

Visual Observations

Visual observations on a timescale of days to weeks indicate that during the calmer periods between the storms, intertidal three dimensional (3D) bed shapes form, such as crescentic bars and mega-ripples (Figure 2). The beach transforms from a dissipative state towards an alongshore non-uniform intermediate state (after Wright and Short, 1984). During the storms, these 3D bed shapes were destroyed, and beach was flattened. This resulted in a ‘beach reset’, which transformed the beach state back into a dissipative beach state with a uniform bar-trough system and no alongshore variability. After each of the three storms, the beach profile showed similarities in shape, suggesting the existence of a general post-storm equilibrium profile. The dune face became a steep scarp after the first storm and remained a scarp for the rest of the campaign. The scarp retreated in the order of metres during the storms. In the period after each of the storms, the complex 3D structures returned in the order of days (Figure 2).

Visual observations during the December storm indicated the presence of plunging breakers that initiated strong alongshore currents. Wave breaking led to the formation of surface rollers which collided with the dune face approximately every 10 s and, after collision, reflected back offshore and interacted with the incident waves. The impact of the colliding waves on the dune face initiated avalanching, with slumps in the order of O(10 cm) deep and O(1 m) wide sliding down periodically every 5-10 minutes (Figure 3).

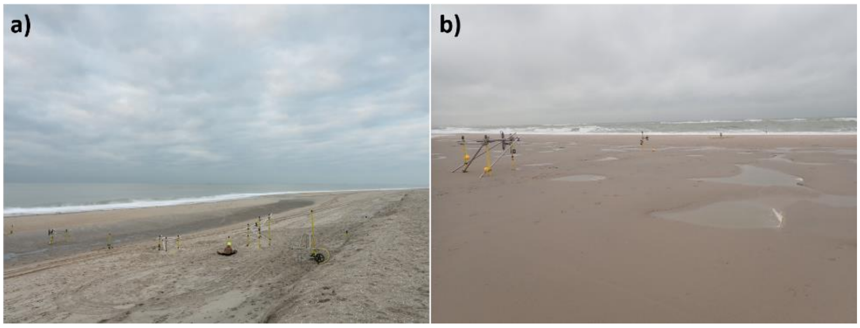

Fig. 2. 3D complexities formed during calmer conditions between storms, such as crescentic bars (a, taken on Nov 27) and mega-ripples (b, taken on Dec 3)

Fig. 3. Dune face during the December storm before (a), during (b) and after (c) wave impact causing a slump to slide down the dune face

Profile Evolution during the December Storm

Figure 4 displays the evolution of the cross-shore profiles of both dunes during the December storm. The December storm consisted of three consecutive high waters (HW's), of which the second was highest with an additional storm surge of 0.74 m on top of an astronomical tide of 1.32 m with respect to NAP (Nieuw Amsterdams Peil, the Dutch ordnance datum). Overall, the post-storm cross-shore profiles show (1) a distinct dune toe which forms the sharp transition in slope from the beach to the dune face, and (2) a parabolic profile running seaward from this newly formed dune toe. Figures 5 and 6 display the bathymetry of both dunes on November 30 and December 2. The depth contours on December 2 are predominantly parallel to the dune foot in the upper segment of the coastal profile, suggesting the post-storm cross-shore profile is mostly uniform in alongshore direction. The total erosion of the dune face is slightly non-uniform in alongshore direction, with larger eroded volumes at the southern ends of both dunes than the northern ends.

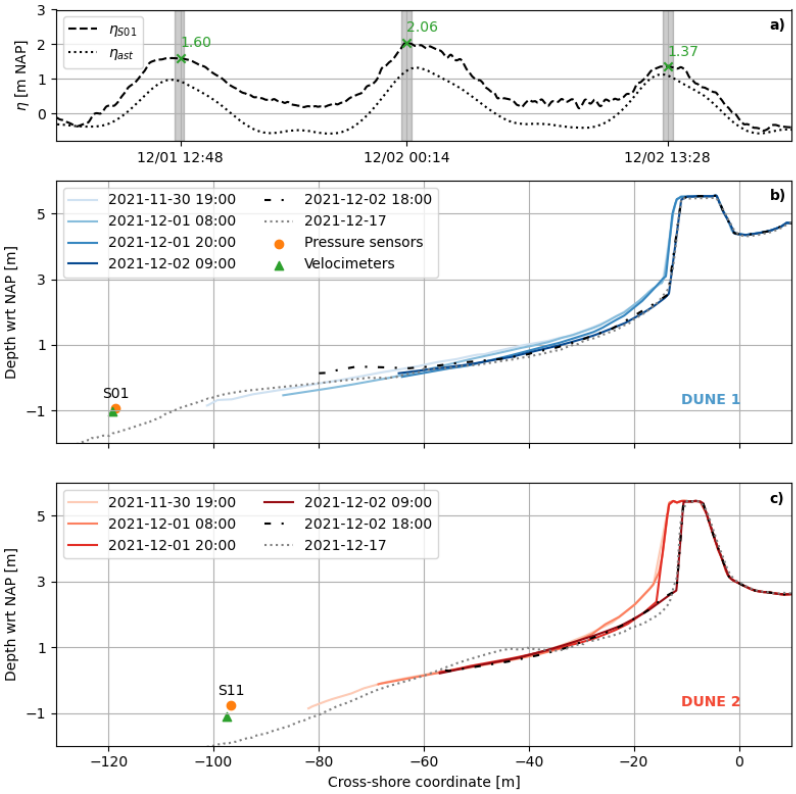

Fig. 4 (a): Water levels recorded by the pressure sensor at station 1 (S01) (dashed), and astronomical tide (dotted). The shaded areas mark the windows on which a spectral analysis will be performed later in this paper. (b) & (c): Profile evolution of both dunes during the HW's of the December storm with the locations of the instruments

Equilibrium theory and a post-storm profile based on the December storm

The visual observations and cross-shore profile evolutions of the previous section suggest the presence of a post-storm equilibrium profile. This section will formulate a post-storm equilibrium profile based on the December storm data. The December dataset is used because the amount of detailed bathymetric surveys conducted during this storm period is largest, allowing an accurate quantification of profile changes between each HW.

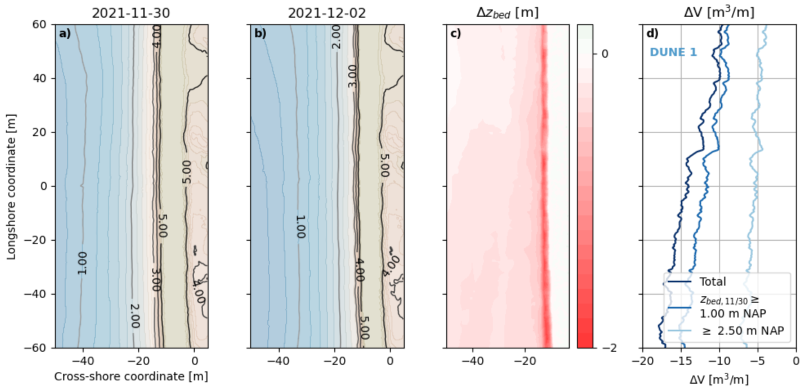

Fig. 5. Bed level on November 30 (a) and December 2 (b) and the difference (c) for dune 1. Panel d displays the erosion volumes along the dune in total, behind the 1.00 m, and behind the 2.5 m contour line of the November 30 survey

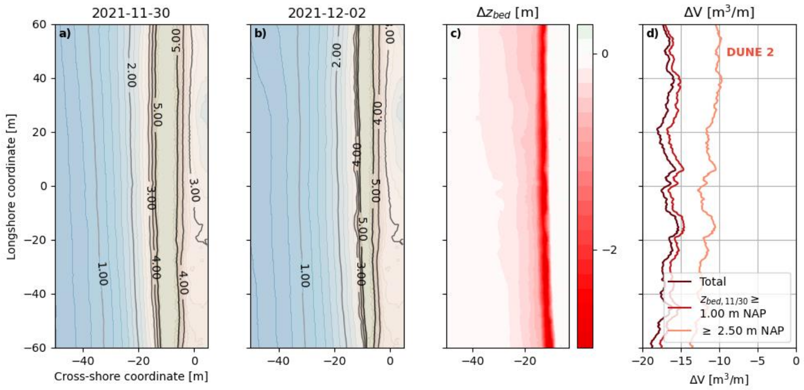

Fig. 6. Bed level on November 30 (a) and December 2 (b) and the difference (c) for dune 2. Panel d displays the erosion volumes along the dune in total, behind the 1.00 m, and behind the 2.5 m contour line of the November 30 survey

The existence of a post-storm profile has been suggested by multiple authors (e.g. Vellinga 1986; Dean 1991), and is based on dune erosion equilibrium theory. This equilibrium theory is based on the negative feedback mechanism between storm hydrodynamics and dune morphodynamics: Incident waves erode sediment from the dune face and beach and transport it offshore, where it settles and dampens the next series of incident waves, thereby reducing erosion from the dune face with time. Due to this mechanism, the dune profile is assumed to converge to a profile which is in equilibrium with the storm conditions.

The vertical position of the post-storm dune toe has been associated to the storm surge level (e.g. Vellinga 1986; van Gent et al. 2008) or a specific elevation above it (e.g. de Winter et al. 2015; van Bemmelen et al. 2020). Figure 4 shows that the dune toe of dune 2 first attains an elevation of 2.38 m NAP on December 1 20:00, and after that an elevation of 2.73 m NAP on December 2 09:00. This corresponds to a water level increase from 1.60 to 2.06 m NAP at S01 (Figure 4), confirming the association of the vertical level of the dune toe and the storm surge level.

The bed elevation with respect to the dune toe, *z(x)*, of the parabolic segment of the equilibrium profile running seaward from the dune toe can be described using a power function as suggested by Bruun (1954) and Dean (1991):

$$z(x) = A \cdot x^{\frac{2}{3}} \tag{1}$$

where x = the seaward directed cross-shore distance from the post-storm dune toe and A = an empirical coefficient depending on sediment characteristics. Here, we will use the power function of Equation 1 to describe the parabolic segment of the post-storm profile, and determine an average A based on best fit of both dune profiles after the 2nd HW. Given that both dunes are built using the same type of sediment, the resulting A should be approximately equal. The available survey data recorded with the GPS runs up to a cross-shore distance of 51.4 m (dune 1) and 45.0 m (dune 2) from the newly formed dune toe (Figure 7). Therefore, the fit will be based on the post-storm dune toe and the cross-shore profile 45 m seaward of this dune toe for both dunes. This yields an average A of 0.21 $\mathrm{m}^{1/3}$ (Figure 7).

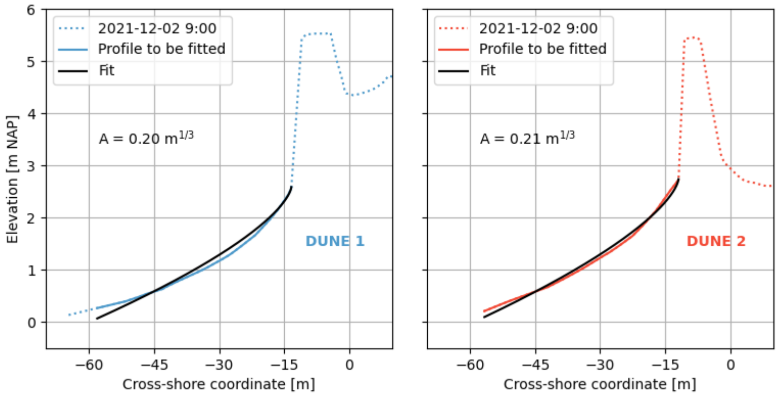

Fig. 7. December 2nd post-storm profiles of both dunes with the segment that is used for the fit and the fit itself to determine the value of A.

Using the equilibrium profile for avalanching estimates

Predicting the shape of the post-storm equilibrium profile

In the previous section, a formulation for a post-storm profile based on the December storm data was presented. It uses a $2/3^{rd}$ power function with an empirical constant *A*. The profile commences at the level of the post-storm dune toe. In this section, we will attempt to predict the position of this post-storm profile based on the incident hydrodynamic conditions.

The field observations indicate that the vertical position of the post-storm profile is associated to the storm surge level. From a physical perspective this makes sense, as the post-storm dune toe is the transition between the relatively drier dune face, and the profile that was frequently flooded during the storm. The flooded profile can be related to the storm surge level because it determines (1) how far short wave energy reaches shoreward and (2) with what magnitude it reaches shoreward. Figure 3 shows that an uprush of even several cm's can result in a slump sliding down the dune face, suggesting that the position of the post-storm dune toe is related to the total water level (TWL). At our field site, the TWL at the dune face (η_{TWL}) can be composed of the tide (η_{ast}), wind setup (η_{win}), wave setup (η_{wav}), and individual swash motion (η_{swa}):

$$\eta_{TWL} = \eta_{ast} + \eta_{win} + \eta_{wav} + \eta_{swa} \tag{2}$$

The astronomical tide is known for the coastal stretch at our field site (Figure 4). The wind setup is computed by subtracting the astronomical tide from the mean water level recorded at both most offshore pressure sensors (S01 and S11). This means that, in our analysis, we assume that the mean water level recorded at these sensors contains the tide and the wind setup only, and we neglect the potential wave induced set-down and set-up at these stations. The wave setup and individual swash motion at the dune face are approximated using Stockdon et al.'s (2006) parametrisation for the setup and maximal swash. For this parametrisation, we use the spectral wave height (H_{m0}) and period ($T_{m-1,0}$) computed at the offshore pressure sensors. The beach slope β is based on the segment of the coastal profile that runs from -1.5 to 1.5 m NAP. The surveys conducted during the December storm did not reach the -1.5 m NAP contour line. Therefore, we resort to two detailed surveys that did run sufficiently far and were conducted before (November 3) and after the fieldwork campaign (December 17), and pick the average slope of the two.

The elevation of the TWL's relative to the elevation of the dune toes during the different HW's are displayed in Figure 8. During the 2nd HW, the TWL comes close to the vertical elevation of the post-storm dune toe for both dunes. Based on this outcome, we assume the TWL to be a reliable estimate for the position of the post-storm dune toe.

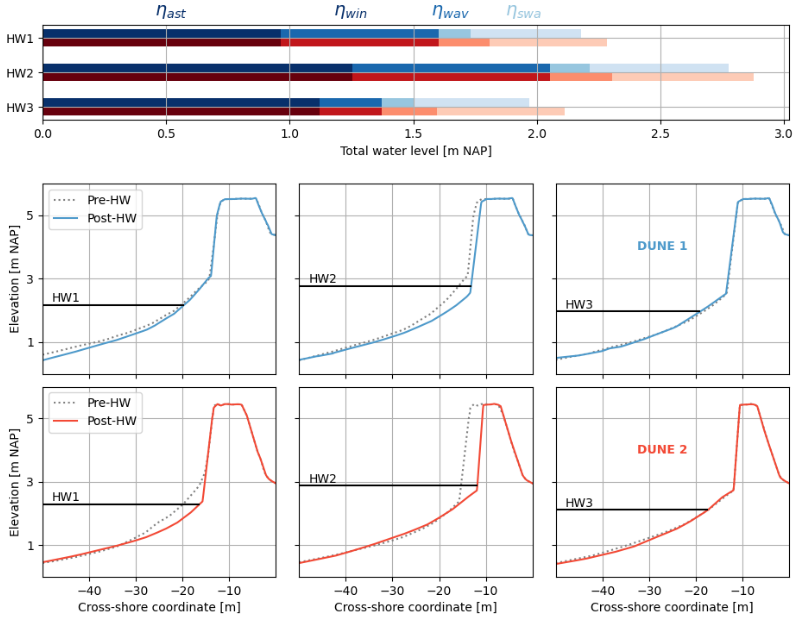

Fig. 8. Total water level for the three HW's in December, decomposed into the different contributions according to Equation 2

The cross-shore position of the dune toe is more difficult to determine beforehand. In equilibrium theory, this position is sometimes based on sediment conservation and a volume balance, in which sediment from the dune face serves as a source of sediment for the underwater post-storm profile (Vellinga 1986; van Gent et al. 2008). In this case, the measured cross-sectional profiles do not run sufficiently far seaward for such an approach. Therefore, in the next section, we will use the shape and vertical position of the equilibrium profile only in the analysis.

Using the equilibrium profile to estimate whether avalanching occurs

Next, we will use the estimated shape and vertical position of the equilibrium profile as an indicator to determine if avalanching does or does not occur. We will resort to the 1st HW of December. During this HW, avalanching does occur at dune 2 and not at dune 1. A closer inspection of both the bed profiles before the 1st HW and their relative elevation to the elevation of the TWL reveals that the profile of dune 2 becomes steeper faster and thereby has a larger water depth in front of the dune. Moreover, if one was to plot the post-storm equilibrium profile derived in this paper, based on the hydrodynamic conditions of the 1st HW and using a dune toe located at the intersection of the TWL and the pre-HW profile, one sees that the profile of dune 1 lies above this equilibrium profile and the profile of dune 2 lies on it (Figure 9).

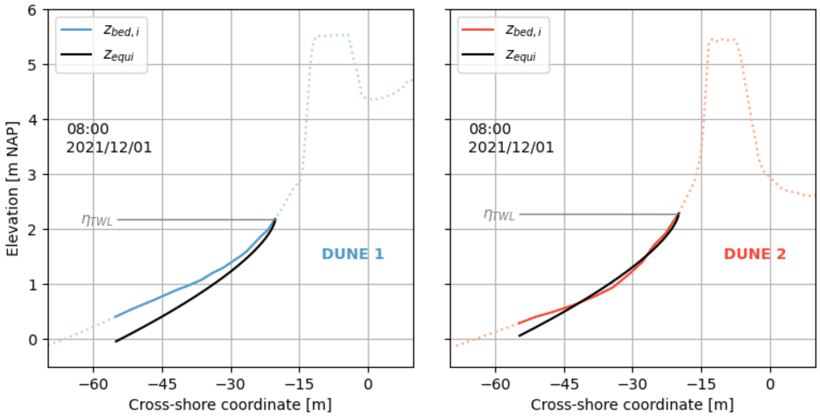

Fig. 9 Mismatches between the pre-storm profile and the post-storm equilibrium profile for the first HW in December

This implies that the mismatch between the pre-storm profile and the equilibrium profile, using the intersection of the TWL and the pre-storm profile as the location of the dune toe of the equilibrium profile, can be used as an indication whether avalanching does or does not occur. By quantifying the total mismatch, it can potentially be used as (1) a condition for avalanching, which might have a certain threshold, and (2) an indication of the total volume that is eroded through avalanching.

Validation of the mismatch theory

To see if the mismatch between the pre-storm profile and the equilibrium profile can be used as a condition for avalanching and an indication of the total volume that is eroded through avalanching, the other storm data and several base cases (cases without avalanching) will be studied. The base cases contain HW's on November 26, December 5, and December 10, which were among the higher HW's recorded during the measurement campaign. The mismatch σ is quantified by integrating the difference between the equilibrium post-storm profile (z_{equi})

and pre-storm profile ($z_{bed,i}$):

$$\sigma = \int_{x[z_i=TWL]-35\ m}^{x[z_i=TWL]} z_{equi}(x) - z_{bed,i}(x)dx \tag{3}$$

σ becomes negative when the pre-storm profile lies above the equilibrium post-storm profile, as was the case for dune 1 during the 1st December HW. It approaches 0 when the two profiles are approximately equal, as was the case for dune 2 during the 1st December HW. If it becomes positive, the equilibrium profile lies above the pre-storm profile. The integral in Equation 3 ranges in cross-shore direction from 35 m before the intersection of the TWL and the pre-storm profile ($x[z_i = TWL] - 35\ m$), to that intersection ($x[z_i = TWL]$). Reason for this is that the January GPS survey of dune 2 only ranges 35 m seaward of this intersection, limiting our computation of the mismatch to only 35 m of the coastal profile. Therefore, to remain consistent in our validation, we will use this stretch for all cases.

To quantify avalanching, we compute the eroded volume of the dune behind the intersection of the TWL and the pre-storm profile. If we assume no water reaches above and beyond this point, all erosion beyond this point can solely be attributed to avalanching.

$$\Delta V = \int_{x[z_i=TWL]}^{0} z_{bed,post}(x) - z_{bed,i}(x)dx \tag{4}$$

Figure 10 displays the mismatches against the erosion volumes through avalanching. The threshold for avalanching seems to be around 0, which can be interpreted as the scenario when the pre-storm profile approaches the equilibrium profile for that storm. Behind this point, a positive correlation can be identified between the positive mismatch σ and the total erosion through avalanching ΔV. If one would assume a linear relationship between the two, the gradient is equal to -0.33, which would imply that for each 3 m^3/m mismatch, 1 m^3/m is expected to avalanche from the dune face.

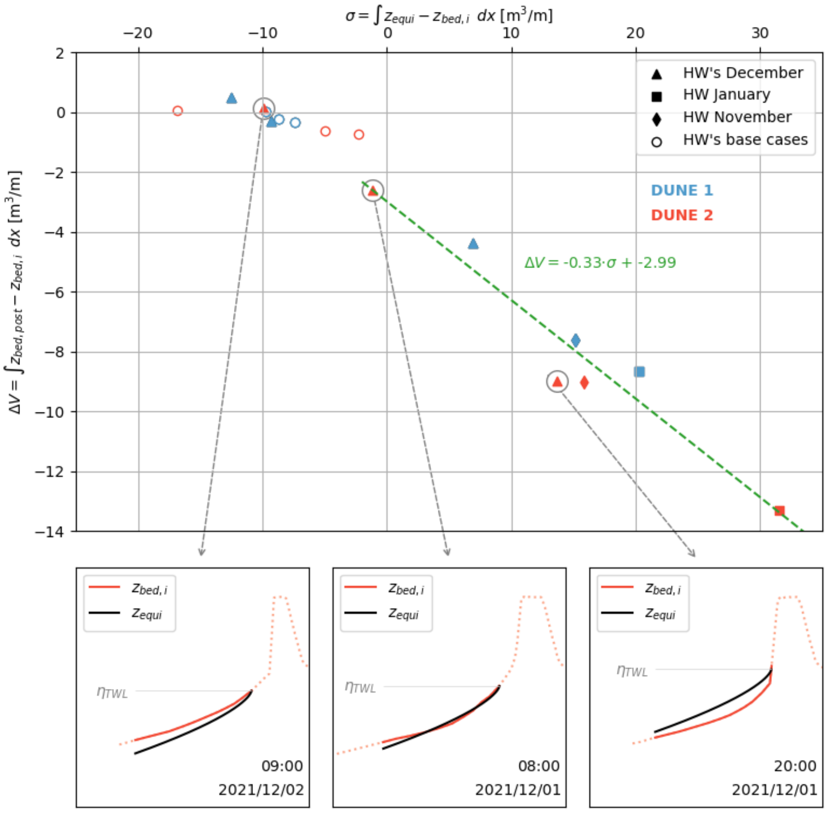

Fig. 10 Profile mismatch plotted against total erosion volumes due to avalanching, according to Equations 3 and 4. The lower panels display scenarios in which the profile (1) exceeds, (2) approximately equates, and (3) subceeds the post-storm equilibrium profile

Discussion

The results presented in this paper suggest that with a relatively simple formulation of a post-storm profile using basic wave parameters, one could estimate whether avalanching of the dune face will occur, and if so, get a first impression of the magnitude. In addition, results from the first high water in December imply that for avalanching to occur, it is not necessary that the total water level exceeds the elevation of the initial dune toe. At dune 2, the total water level was lower than the initial dune toe, but avalanching still occurred. During the high water, the dune toe retreated, but actually lowered with respect to its pre-storm position.

It should be noted, however, that the method described in this paper has several shortcomings. One for instance, is that the equilibrium profile used for the mismatch reaches only 35 m seaward, while existing literature talks of equilibrium profiles which reach much further seaward (e.g. van Gent et al., 2008). It could very well be that the upper 35 m is in equilibrium with the hydrodynamic conditions, but the segment further seaward is not, which could lead to scenarios during which avalanching would still occur. This could be the case for more extreme storms than the ones handled here, as more extreme storms generally have longer equilibrium profiles (van Gent et al. 2008). Another shortcoming is that the temporal component has not been incorporated in this method. We use a total water level based on the maximum surge level. This maximum level should persist for a sufficiently long time to allow multiple waves to collide with the dune face during the storm and force sediment to slide down through avalanching. In our campaign, this was the case.

Nevertheless, the results presented here show that a relatively simple method, which is computationally cheap, can be used to get a first estimate whether avalanching occurs and with what magnitude. The complexities mentioned above could be incorporated, but this would come at the expense of the simplicity of the method.

Conclusions

This paper presented observations of a field experiment which took place from November 7th 2021 to January 7th 2022 along the Dutch Coast near Kijkduin. Two artificial dunes were constructed and exposed to three storms. Results suggest that the cumulative volume eroded through avalanching during a single high water is positively correlated with the profile mismatch between the pre-storm profile and a ‘storm equilibrium profile’, described by a 2/3rd power law, an empirical coefficient A, and the total water level. The total water level is estimated using the parameterization of Stockdon et al. (2006), which uses the beach slope, wave height, and wave period as input. Avalanching commences when the mismatch becomes larger than approximately 0 m^3/m, after which 1 m^3/m of sediment erodes from the dune face for every 3 m^2 mismatch. In addition, during the 1st December HW avalanching occurred at dune 2 even though the elevation of the total water level did not exceed the initial elevation of the dune toe. This implies that a total water level that exceeds the initial elevation of the dune toe is not a requisite for avalanching and a collision regime to occur, which contradicts conventional definitions of dune erosion regimes.

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