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CHAPTER 235

MECHANISM AND CALCULATION OF SAND DUNE EROSION BY STORMS

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ABSTRACT: Dunes constitute a central element in shore-protection designs aimed at preventing inundation and erosion of the upland by storms. In the present study, the dune-erosion mechanism is investigated through field observations of the performance of sand dunes under storm action in Japan and in the United States. The observations are quantified by analysis of three test series carried out in the SUPERTANK project. The SUPERTANK data set includes tests on erosion of an uncompacted and a compacted near-vertical dune by random waves. The SBEACH numerical model of dune erosion and profile change is modified to erode dunes by the force of incident waves. This sediment can then supply the profile change model that demands offshore movement of sand in response to the occurrence of storm waves and elevated water level. The simulations show good agreement with the erosion measured at SUPERTANK for the uncompacted and the compacted dunes.

INTRODUCTION

Dune design is a central element in shore-protection projects aimed at preventing inundation and erosion of the upland by storms. In the United States and some other countries, the performance of protective dunes is often estimated with the Kriebel and Dean (1985) model or the Larson and Kraus (1989) (SBEACH) model of storm-induced beach erosion. These models operate under the assumption that erosion of the beach and dune complex is controlled by the demand for sand in the surf zone to satisfy establishment of an equilibrium profile under the impressed storm water level and waves. The demand, or, cross-shore sediment transport capacity, is estimated from the difference in wave energy dissipation between the existing profile and an assumed equilibrium profile shape. Conceptually, in such a demand-and-supply model (demand model), if a dune exists on an equilibrium beach profile for a given storm condition, little dune erosion is expected to occur. Clearly, however, a dune will erode if it is subjected to violent wave action almost independently of the equilibrium profile dynamics occurring offshore. Resolution of this problem is discussed here.

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In the present study, the dune-erosion mechanism is investigated through field observations of the performance of sand dunes under storm action in Japan and the United States. These observations are quantified by analysis of test series from the SUPERTANK Data-Collection Project (Kraus et al. 1992, Kraus and Smith 1995, Smith and Kraus 1996). The data set includes two tests involving erosion by random waves of 0.8-m high, nearly vertical dunes composed of 0.23-mm median-diameter sand. One test involved an uncompacted dune (SUPERTANK Test ST_50) and the other a compacted dune (ST_60). Complete time series of the water-surface elevation are available from the offshore to the face of the dune, although only breaking waves were employed here to compute the impact parameter and related volume of dune erosion.

Dune erosion is calculated as a function of a wave-force parameter (Sunamura 1977, Fisher and Overton 1984). Material eroded from the dune is supplied to the nearshore where profile change is calculated through equilibrium-profile concepts. Therefore, we call the methodology a *supply-and-demand* dune erosion and profile change model. This paper describes different mechanisms of dune erosion and the new supply-and-demand model. The model is then tested to simulate dune erosion measured at SUPERTANK.

MECHANISM OF SAND DUNE EROSION BY STORMS

In this paper, we consider dune erosion produced by impact forces of waves incident nearly normal to the shore, a cross-shore transport process that is assumed to be two dimensional. This assumption is supported by the uniform dune recession commonly observed after large storms along kilometers of shore despite longshore variations in coastal structures and offshore bathymetry. However, we note the possibility of the action of shearing forces exerted on dunes by waves and associated currents passing tangentially to the shore. Such a situation occurs by waves generated by ships passing dunes in narrow channels. Shearing erosion is not considered further here.

Field Observations

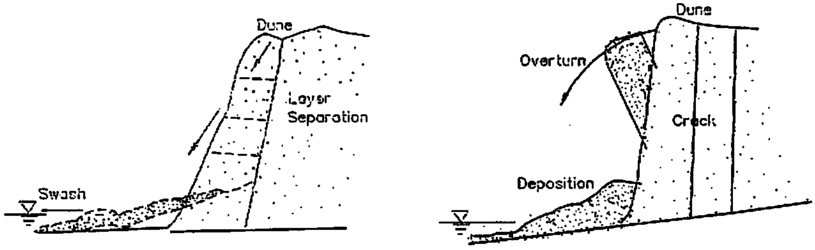
Sunamura (1992) has described basal erosion and mass movement (failure or erosion) of cliffs on rocky coasts as four types: falls, topples, slides, and flows. In the present study, the authors have documented three types of erosion mechanisms of sand dunes by wave impacts during storms or strong wave action. The cross-shore dune-erosion mechanisms, schematized in Fig. 1, are classified as (a) layer separation, including layer separation and overturning, (b) notching and slumping, and (c) sliding and flowing.

Layer separation. Layer separation typically occurs if a near-vertical dune face is subjected to wave impact. Over the duration of a certain number of impacts, a vertical fault line (crack) develops, and this outer layer gradually separates (typically 30 to 50 cm thick) from the landward portion of the dune. As it separates, the outer layer detaches from the main body of the dune, becomes unstable, and either collapses suddenly (Fig. 1a) or tilts forward and overturns (Fig. 1a′).

Notching and slumping. Severe notching tends to occur if a dune slope is nearly vertical, permeated by roots, highly compacted, or composed of rocks such as a rocky cliff. Notching is limited to the elevation of wave attack and, after the notch is cut sufficiently deep into the base of the dune, the overlying sand column collapses. (Some notching may also occur during layer separation, but it is not the dominant factor in the collapse of the separated layer.) The material from the collapsed dune face is deposited in front of the new dune face.

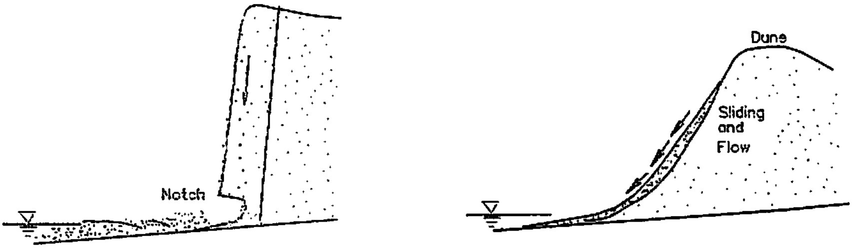
The width of sand deposition at the foot of the dune face is less than that of layer separation, which involves the overturning and sliding of a layer.

Sliding and flowing. Sliding and flowing occur on uncompacted gently sloping dunes that have a face slope close to the angle of repose of the sediments forming them. In this situation, modest wave impact at the base of the dune or even pelting by rain or exposure to strong wind can cause a thin layer of sand to run down the slope. It is expected that this mode of dune erosion does not cause severe dune recession in a short period of time; however, this mechanism tends to steepen the dune face and a resultant steeper dune slope will probably trigger layer separation or notching and slumping under storm conditions.



(a) Layer separation

(a') Layer separation and overturning



(b) Notching and slumping

(c) Sliding and flowing

Fig. 1. Dune erosion mechanisms by cross-shore processes.

SUPERTANK Dune-Erosion Tests

The erosion mechanism was quantified by using profile response measurements made at the SUPERTANK project. The particular tests analyzed here concern profile steepening and dune erosion. These test series involved random wave incident to a near-equilibrium profile, and to uncompacted (loose sand) and compacted near-vertically faced dunes. Complete time series of the water surface elevation are available from the offshore to the dune face (Smith and Kraus 1995); however, in this study, as a preliminary and less calculationally intensive step, only wave-related quantities calculated at the breaker line were used.

The three SUPERTANK tests discussed in the present study were ST_10 (erosion of an equilibrium profile), ST_50 (uncompacted dune), and ST_60 (compacted dune). The waves were run in bursts of 10-40 min, and conditions were sometimes changed between bursts, for which representative waves are as follows:

Test Number	Significant Wave Height, m	Peak Spectral Period, sec
ST_10	0.8	3.0
ST_50	0.5 - 0.8	6.0 - 3.0
ST_60	0.5 - 0.7	6.0 - 3.0

Erosion above a near-equilibrium profile. For SUPERTANK Test ST_10, random waves and monochromatic waves were generated to act on an initial idealized sub-aqueous equilibrium beach profile. Evolution of the beach profile is shown in Fig. 2. Four series of slope steepening (scarping) events occurred in the test. The profile in the swash zone steepened and maintained a constant angle at the second through fourth wave-burst events, while the upper beach face receded. The slope of the upper beach face is $\tan\beta \approx 0.89$, slightly less than that of a one-to-one slope (45 deg) typically specified in the Kriebel and Dean (1985) model. The slope of the upper beach face appears to exert control on the speed and volume of upper beach erosion.

Fig. 3 shows the process of profile steepening and scarp generation at the first and second wave-burst events of the erosion processes shown in Fig. 2. The beach-face slope steepened, and the swash waves carried the sediment offshore while lowering the beach face. Once the slope of the upper beach face approached the angle of failure (avalanching), the upper portion of beach face collapsed and the sediment was deposited in front of the scarp. Thereafter, successive swash waves transported the sediment seaward that was supplied from the upper beach face. As the beach face was lowered by erosive swash waves, swash uprush intensely impacted the steep beach face, again causing avalanching. These erosion processes in the swash zone continued until the upper beach face was no longer vulnerable to swash waves. This test series demonstrates that the upper beach face behind a sub-aqueous near-equilibrium beach profile can be eroded by swash wave activity until it also achieves equilibrium with the water level and swash.

Dune erosion tests. Two dune-erosion tests were conducted at SUPERTANK, one for a dune formed of sand without compaction (ST_50) and the other for an artificially compacted dune (ST_60). The dune was compacted by applying a pavement vibrator for approximately 2 hr. Both dunes were subjected to short-period high waves. The water level was lower at the beginning of the tests and higher at the end of the tests (Kraus and Smith 1995, Smith and Kraus 1996). In the dune-erosion tests, the dune face tended to recede in parallel to itself, as shown in Fig. 4. Video records made during SUPERTANK indicate both the uncompacted and compacted dunes eroded primarily by layer separation. In all situations observed in the field and at SUPERTANK, dune faces tended to recede in parallel to themselves.

This coherent behavior of dune evolution illustrates the consistency and reproducibility of the dune-erosion mechanism. The sediment supply from the dune to the swash zone by either the layer-separation or notching-and-slumping erosion mechanisms was injected virtually instantaneously (order of one wave period) when a wave or backwash swept the eroded sediment toward the swash zone.

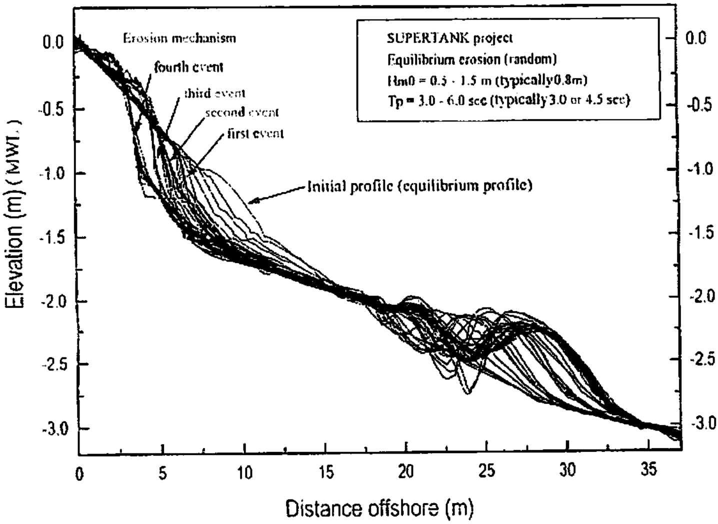


Fig. 2. Profile change on a near-equilibrium beach (ST_10).

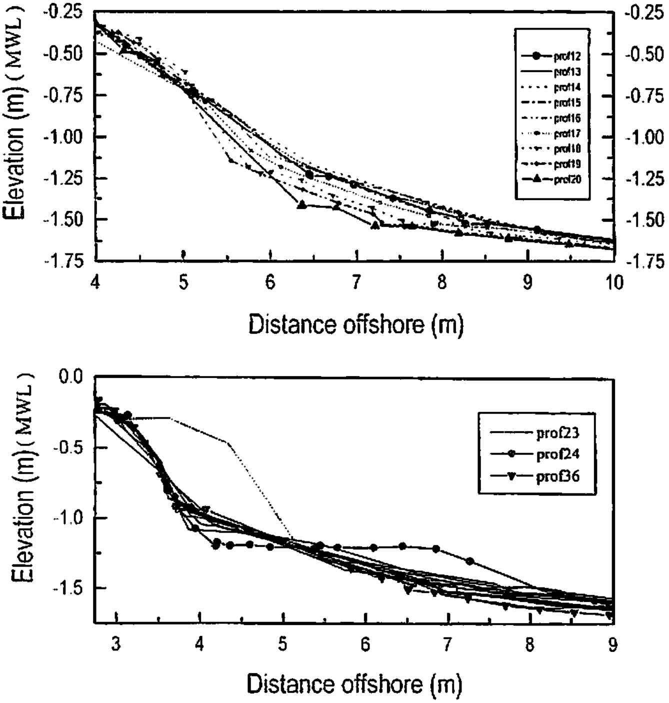


Fig. 3. Beach face steepening and scarp generation (ST_10).

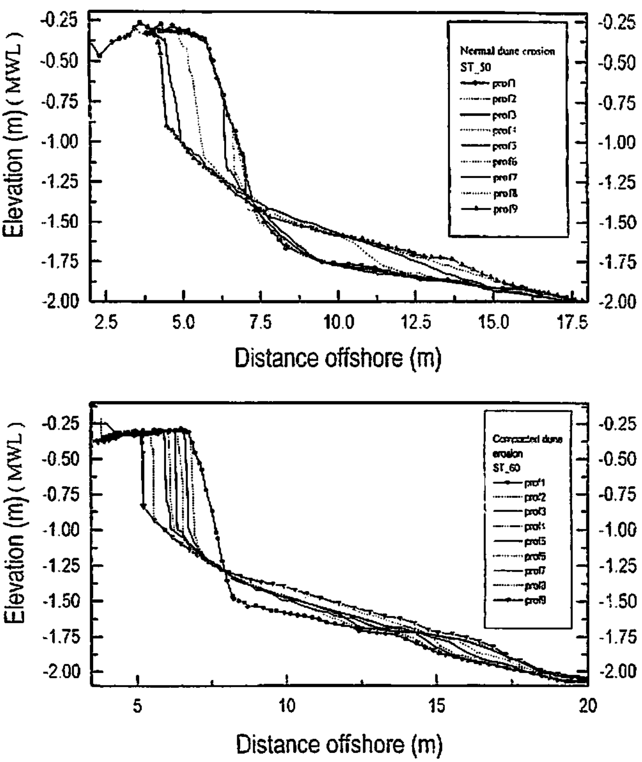


Fig. 4. Erosion of uncompacted (ST_50) and compacted (ST_60) dunes.

The volume of erosion of the compacted dune was less than that of the uncompacted dune, despite the slope of the compacted dune being steeper than that of the uncompacted dune during the erosion, as shown in Fig. 4. Compaction altered the strength of the dune and the volume of eroded material, thickness of layer separation, and angle of slope failure. It is clear that a compaction coefficient should be introduced in future studies of profile evolution.

DUNE EROSION MODEL

A numerical model of dune erosion was developed in the present study that simulates the impact force of individual waves on the dune face. Research conducted at Tuskuba University, Japan, for cliff erosion (see Sunamura 1977, 1992) and at North Carolina State University for sand dunes (see Fisher and Overton 1984, Fisher et al. 1986, and Overton et al. 1994) has advanced this approach. The impact-force and dune-erosion model was incorporated as a sub-model of SBEACH (Larson and Kraus 1989, Nishi et al. 1991) and employs the wave model of SBEACH supplemented by a swash model that includes bore velocity and height to estimate the impact parameter. The total model consists of a wave transformation model, cross-shore sediment transport model in the surf zone, and a sediment supply model from the dune.

In SBEACH, wave transformation in the surf zone is computed based on the Dally et al. (1985) model. For describing random wave incidence, it was assumed that the heights of individual waves follow a Rayleigh distribution and the wave period for an individual wave corresponds to an average wave period. The wave height of individual waves was computed by a Monte Carlo method (Larson and Kraus 1991).

Profile Zonation

Because the model computes the sediment transport in the surf zone and sediment supply and transport from the dune by different mechanisms, the beach and dune systems were divided into three zones as the (a) dune, (b) swash zone, and (c) surf zone (Fig. 5). This profile zonation modifies that of the original SBEACH model at the dune. The maximum runup or swash elevation Z_r is defined as a function of the surf-similarity parameter as given by Eq. (1) (Larson and Kraus 1989)

$$\frac{Z_r}{H_o} = 1.47\left(\frac{\tan\beta}{\sqrt{H_o / L_o}}\right)^{0.79} \qquad (1)$$

where H_O = deep-water wave height, and L_O = deep-water wavelength by linear-wave theory.

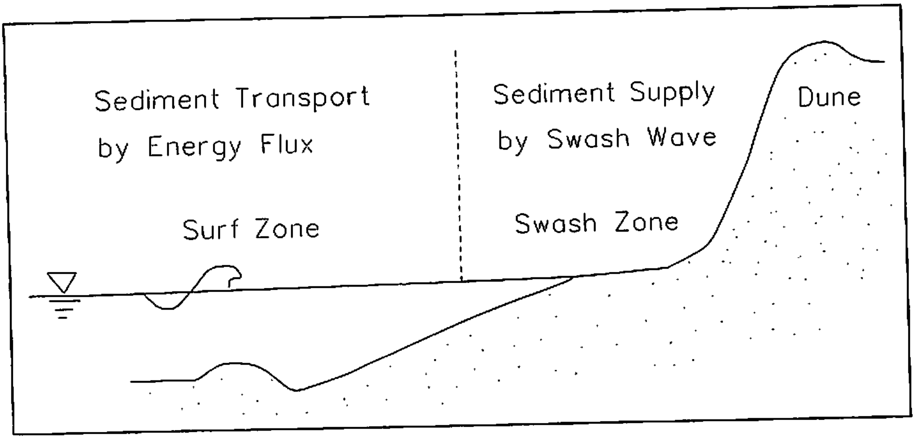


Fig. 5. Schematic diagram of dune and beach system.

Calculation of Sediment Supply from Dune

As storm waves approach the beach, bores impact the dune face and cause erosion. Thus, the volume of dune erosion during a storm or by waves that reach the dune face during times of elevated water level should be related to the force of wave impact. Sunamura (1977) parameterized this impact wave force by the incident wave height in study of rocky cliff erosion. A strong correlation between wave impact force and sand dune erosion was found by Fisher et al. (1986) for artificially constructed sand dunes in the field and by Overton et al. (1994), who obtained a correlation between the force of impacting waves and volume of dune erosion for the compacted dune at SUPERTANK.

The wave-force impact parameter is derived heuristically by considering the situation shown in Fig. 6 and the rate of change of wave momentum. The mass m of water per unit length of crest in a bore of height H and length L moving in shallow water of average depth h over the length of the wave is given by

$$m \approx \frac{1}{2}\rho_w HL = \frac{1}{2}\rho_w HT\sqrt{gh} \tag{2}$$

where ρ_w = density of water, T = wave period, g = gravitational acceleration, and $(gh)^{1/2}$ is the celerity of the wave. The wave impact force per unit length of dune is estimated by multiplying the mass m by the deceleration $(gh)^{1/2}/T$ resulting from the wave striking the dune and stopping in the time interval of the wave period T. This derivation suggests consideration of a cumulative wave-force impact parameter I defined by

$$I \equiv \rho_w gh H\frac{\Delta t}{T} \tag{3}$$

where Δt is the time interval or duration over which the waves impact, and the ratio $\Delta t/T$ is the number of waves. The ratio $\Delta t/T$ can be easily modified to describe random waves by summing the contributions of the individual waves of different height, period, and speed. The impact parameter has the dimensions of Newtons per unit wave crest or dune width.

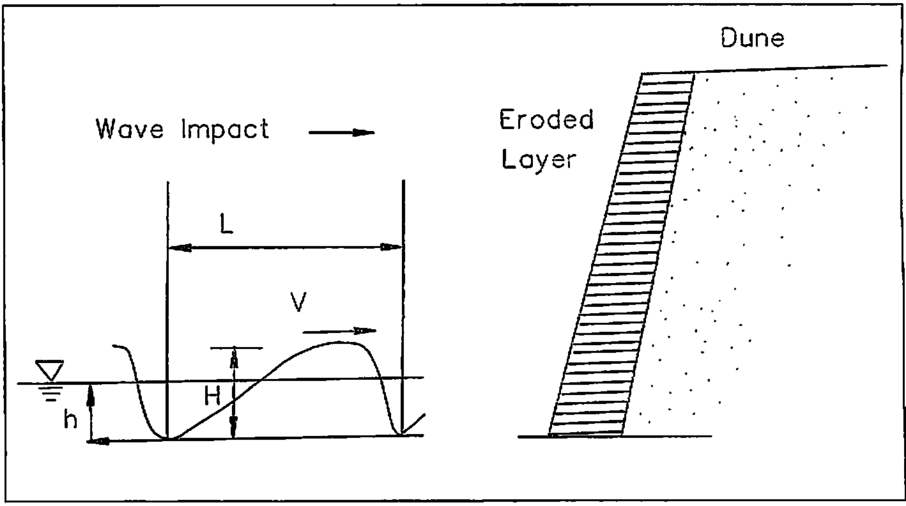


Fig. 6. Schematic diagram for the wave impact parameter.

For dimensional homogeneity it is convenient to work with the weight per unit width alongshore of the eroded material $W_E = \rho_S (1 - p) g V_E$, where ρ_S = density of the sand comprising the dune, p is the porosity of the sand (0.4 for uncompacted sand, 0.2 estimated for the compacted sand dune), and V_E is the volume of material eroded from the dune. The density and, therefore, the porosity, of the uncompacted and compacted dunes should be different.

Analysis of the data computed from the average of the impact forces indicated a linear relationship as shown in Fig. 7 and resulted in the empirical equation for the weightper unit width $(W_E)_U$

$$(W_E)_U = 0.81(I - I_{crit}) \tag{4}$$

for the uncompacted dune, and the weight $(W_E)_C$

$$(W_E)_C = 0.50(I - I_{crit}) \tag{5}$$

for the compacted dune. In the above, the critical wave impact parameter for inception of erosion I_{crit} is set to zero at the present time because of uncertainty in its value.

These equations and Fig. 7 show that waves with the same impact parameter erode a compacted dune less than a uncompacted or unconsolidated dune. An engineering lesson from this result indicates that greater erosion protection would be gained through construction of dunes by wetting the sand for consolidation and compacting them with vibrating compactors, rollers, and other heavy equipment. The above result was obtained from a limited number of tests available from the SUPERTANK project, and further verification needs to be done to refine the result.

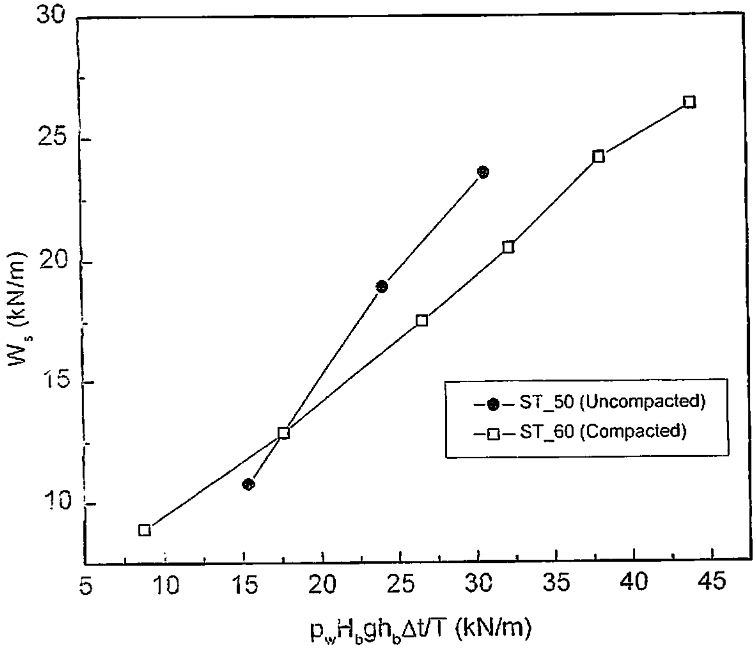


Fig. 7. Impact parameters for uncompacted and compacted dunes at SUPERTANK.

NUMERICAL MODEL OF DUNE EROSION

From the above discussion, the volume of sand eroded from a dune can be calculated as a function of time through knowledge of the incident waves and the wave-force impact parameter. Thus, the amount of sand supplied to the profile by the dune is known. As the next step, an assumption must be made as to how the sediment enters the swash zone or surf zone where other transporting mechanisms are operating. Here, it is assumed that sediment is introduced to the swash zone at a uniform rate within each time step of the model according to the supply available from the dune at that time step. A typical calculation time step in the model is 1 min, and the grid cell size on the foreshore is 0.1 m. Uniform distribution of sediment supply agrees with visual observations made at SUPERTANK and inferences from field observations, and it is also reasonable in a time-average sense. The structure of the numerical model does not preclude a more detailed description of the sediment-supply procedure to the swash zone and can be modified as understanding improves.

Dune Erosion Model (Supply)

We found above that a dune face recedes with a certain angle in accordance with the amount of compaction. Nearly vertical dune faces produced by erosion during storms are commonly observed in the field, in particular for well-established dunes presumably compacted by natural settling and wetting. In the SUPERTANK project, the angles of the dune face were approximately 68 deg for the uncompacted dune and 87 deg for the artificially compacted dune, as shown in Fig. 8. The irregularity in dune-face angle through time for the compacted dune may have been caused by uneven compaction close to the initial dune face. In the model simulations described below, it is assumed that the slope of the dune face is 68 or 87 deg depending on the amount of compaction.

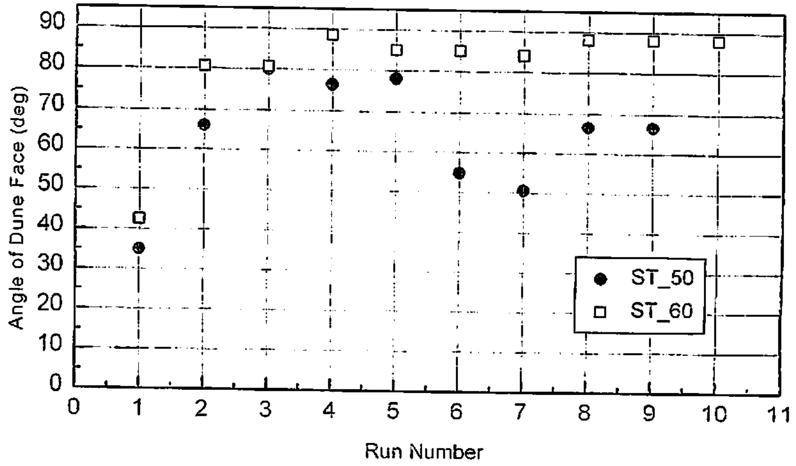


Fig. 8. Angle of dune face for uncompacted and compacted dunes at SUPERTANK.

As determined from the SUPERTANK data, the volume of dune erosion can be estimated by the duration and intensity of wave impact, which yields an eroded volume ΔV_E per unit longshore width of dune. A corresponding recession distance can be computed by assuming the dune face retreats a certain distance and at a certain angle to a baseline. The baseline is a vertical datum located at the toe of the dune. In the model, the volume of sand eroded from the dune is distributed uniformly as a thickness Δh_S over a distance X_S, which is taken to be an effective distance of the swash zone extending from the toe of the dune at the present time step to some depth defining the seaward limit of the swash zone, arbitrarily set to 0.3 m or a comparable value (Larson and Kraus 1989). Then we have

$$\Delta h_s = \frac{\Delta V_E}{X_S} \tag{6}$$

for the thickness of the sand layer.

Profile Change Model (Demand)

In the SBEACH model, sediment demand or the potential transport rate in the surf zone is calculated based on the dissipation of wave energy flux originally derived by Dean (1977) and implemented by Kriebel and Dean (1985) in dune-erosion modeling. In the surf zone, SBEACH computes the cross-shore sediment transport rate as

$$q = K\left(D - D_{eq} + \frac{\varepsilon}{K}\frac{\partial h}{\partial x}\right) \tag{7}$$

where K = empirical transport rate coefficient, ε = empirical coefficient controlling the strength of the slope-dependent transport rate term, and the energy dissipation per unit water volume D is

$$D = \frac{1}{h}\frac{\partial F}{\partial x} \tag{8}$$

in which F is the wave-energy flux. The dissipation for a profile in equilibrium with the existing waves and water level D_{eq} is given by (Dean 1977)

$$D_{eq} = \frac{5}{24}\rho_w g^{3/2}\left(\frac{H_b}{h_b}\right)^2 A^{3/2} \tag{9}$$

where A is an empirical "shape" parameter related to the form of the equilibrium profile and the grain size of the beach (Moore 1982).

In SBEACH, the transport rate in the surf zone as given by Eq. (7) is only calculated if $D > D_{eq} - \varepsilon/K\ \partial h/\partial x$, and the transport direction as onshore or offshore is determined by a separate function (Kraus et al. 1991). As originally developed (Larson and Kraus 1989), SBEACH calculates cross-shore transport rates in four zones, with a linear rate employed in the swash zone and a magnitude as determined by matching with Eq. (7) at the swash zone and surf zone interface. Material moved from the dune to the swash zone by the supply dune-erosion model is then moved offshore by the swash and surf zone transport.

Numerical Simulation of Dune Erosion at SUPERTANK

A numerical simulation was conducted to calculate dune erosion for Test ST_60 (compacted dune). The empirical dune-erosion predictor incorporated in the model was developed based on the SUPERTANK data and impact parameter, as described above. Therefore, the simulation is not a verification of the model; rather, it demonstrates the validity of the numerical scheme and behavior of the supply-and-demand procedure that connects the dune to the profile.

Fig. 9 shows the profile change simulated by applying the (standard) demand model, which can be compared to the profile change simulated by applying the supply-and-demand model, Fig. 10. The demand model underestimates the dune erosion for which the compacted dune is located on a beach profile in near equilibrium with the impressed waves.

We note in this paragraph independent contemporaneous work involving SUPERTANK Tests ST_10, ST_50, and ST_60. Wise et al. (1996) report comparisons of SUPERTANK measurements (and field measurements) and calculations performed with the most recent version of SBEACH operated by the US Army Engineer Waterways Experiment Station (WES), for which default calibration parameters (K and ε) were specified (the calibration parameters were not optimized for the individual tests). The most recent WES version of SBEACH incorporates sophisticated random-wave and cross-shore sediment transport models not applied in the version used in the present study. The WES version is still a demand model. For equilibrium Test ST_10, erosion of the foreshore was obtained by Wise et al. for random waves with the new WES version of SBEACH. For the dune erosion tests, the WES version well reproduced erosion of the uncompacted dune (ST_50) and overpredicted dune erosion for the compacted dune (ST_60). Wise et al. comment that "The difference in model predictions between the two dune cases might be expected due to greater erosion resistance associated with the compacted sediment which is not accounted for in SBEACH." This comment was verified in the present work.

CONCLUDING DISCUSSION

Three types of dune erosion mechanisms were identified through field observations as: (a) layer separation, (b) notching and slumping, and (c) sliding and flowing. The layer-separation mechanism was quantified by analysis of the SUPERTANK dune erosion tests by which the eroded volume could be related to the cumulative wave impact force. The degree of compaction was found to be a significant parameter that decreases the potential for dunes to erode. Therefore, an economic benefit might be gained by compacting artificially placed dunes to improve their performance as shore protection. The supply-and-demand model developed can simulate dune erosion and beach profile change based on representations of the hydrodynamics and sediment transport acting in each region and provides, in principle, a more accurate representation than existing demand models, especially in applications where the beach profile is approximately in equilibrium with the impressed storm waves and water level. The present study suggests ways through which geotechnical considerations might be incorporated in dune erosion modeling to both account for compaction and introduce supply and demand considerations.

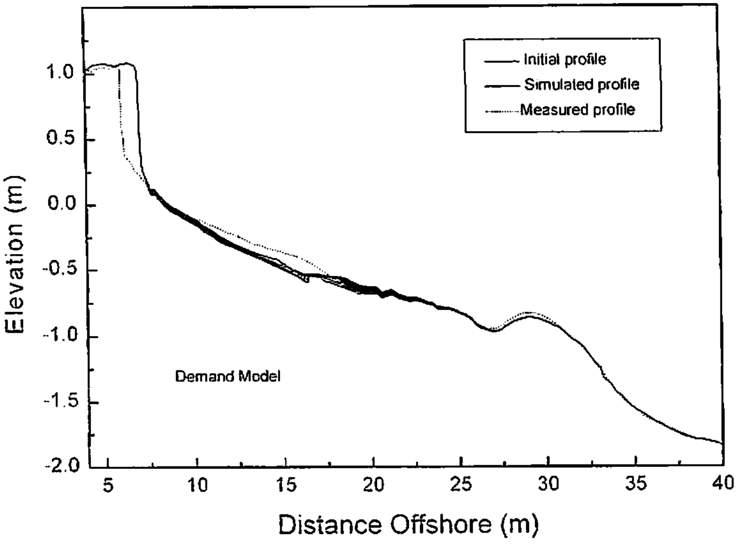


Fig. 9. Simulation for compacted dune (ST_60) by demand model.

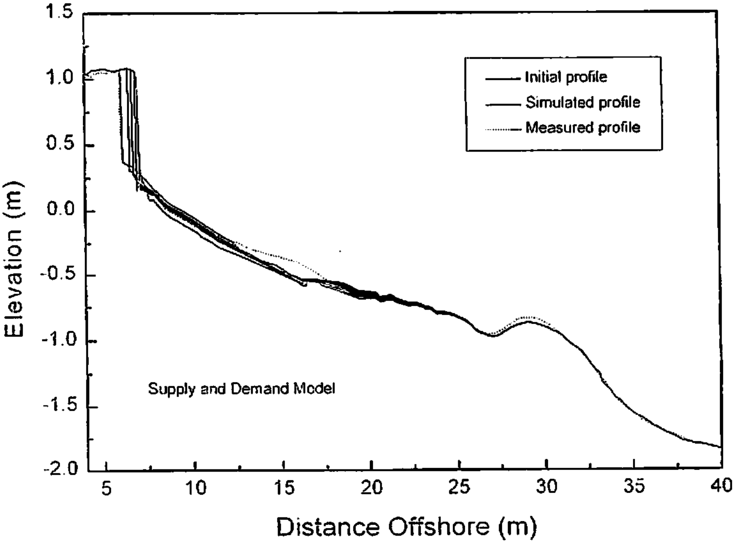


Fig. 10. Simulation for compacted dune (ST_60) by the supply-and-demand model.

ACKNOWLEDGEMENTS

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