CHAPTER 174

ADVANCES IN NUMERICAL MODELING OF DUNE EROSION

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INTRODUCTION

Estimating dune erosion during severe storm events continues to be a major coastal engineering problem. In the United States, for example, numerous state and federal regulatory programs now require an estimate of the erosion caused by the 100-year hurricane or extratropical storm. In addition, most beach replenishment projects include storm protection berm and dune systems that must be sized to survive some design storm event.

Given these requirements, methods of predicting dune erosion must continue to evolve and improve. Before the early 1980's, most dune erosion methods were based on geometrical arguments. Since then, however, the two most widely-used methods for predicting dune erosion in the United States have been the empirical model of Vellinga (1983, 1986), based on extensive large wave tank tests, and the numerical model of Kriebel and Dean (1985), based on a finite-difference solution of simplified governing equations. A recent model by Larson and Kraus (1989) is also being used by the Corps of Engineers and is based on governing equations similar to those used in the Kriebel and Dean model. These models have been successful largely because of their simplicity in describing the macroscopic cross-shore profile changes without considering details of surf zone hydrodynamics or sediment transport.

For widespread application in the U.S., however, it is generally recognized that neither the Vellinga model nor the Kriebel and Dean model are sufficiently general to accommodate all beach profile, storm surge, and wave conditions of interest. The most critical limitation on both models is that they have been developed for the case of high dunes that extend infinitely landward and which

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are not overtopped by storm surge or wave uprush. In the U.S., however, most coastal locations do not have such massive frontal dunes. Dune erosion models must, instead, be capable of simulating profiles with low dunes that may be overtopped, narrow dunes that may be eroded completely, multiple dune ridges that may erode sequentially, or dunes that are backed by shore protection structures.

In this paper, revisions to the Kriebel and Dean model are reviewed that remove some of the previous limitations. These modifications, primarily in the onshore boundary region, enable more realistic simulation of a variety of beach and storm conditions while retaining the general simplicity of the original model.

BACKGROUND

The original Kriebel and Dean erosion model predicts the time-dependent evolution of beach and dune profiles based on time-histories of storm surge and wave height, as described by Kriebel and Dean (1984, 1985). This model is based on Dean's (1977) equilibrium profile theory, in which the profile form that will ultimately be attained if water level and wave conditions are held constant indefinitely is of the form

$$h = A\ x^{2/3} \tag{1}$$

where h is the water depth at a distance x from the shoreline. This form is consistent with the uniform dissipation of wave energy per unit volume in the surf zone based on shallow water spilling breaker assumptions. The parameter, A, is related theoretically to a value of the energy dissipation per unit volume, D_E, which must occur everywhere across the profile when the system is in equilibrium. Dean (1977, 1987), Moore (1982) and others have then related A empirically to the median sand grain size.

The time-dependent profile response is then simulated by solving two simplified governing equations in finite-difference form. These are the continuity equation

$$\frac{dx}{dt} = -\frac{dQ}{dh} \tag{2}$$

and a simplified expression for the net sediment transport rate at any location in the surf zone

$$Q = K\ (D - D_E) \tag{3}$$

based on the difference between the energy dissipation at any location, D, and the equilibrium value, D_E.

Based on shallow water spilling breaker assumptions, the energy dissipation per unit volume is given by

$$D = \frac{1}{h} \frac{dF}{dx} = \frac{5}{16} \rho g^{3/2} k^2 h^{1/2} \frac{dh}{dx} \qquad (4)$$

where k is the ratio of the breaking wave height to the water depth, assumed to be 0.78. Based on equation (4), energy dissipation is a function only of the local water depth in the surf zone such that the sediment transport rate across the surf zone is dictated only by the shape of the profile relative to its equilibrium shape for a given water level.

The rate parameter, K, in equation (3) is the only free parameter in the governing equations and is used to calibrate the model. In the recent model by Larson and Kraus, equations (1) and (3) are modified to also include a gravity driven slope-dependent term, at the expense of introducing an additional parameter which then must be empirically determined. In the original model by Kriebel and Dean (1984, 1985), the value of K was adopted from a previous study by Moore (1982). An initial verification was then carried out in a simulation of erosion during Hurricane Eloise. In this case, one representative or average profile was used for the initial condition and computed erosion volumes were found to agree reasonably-well with county-wide average erosion values. Steepening of the dune during erosion was not simulated, however, so that predicted recession of specific dune elevation contours did not agree closely with observed values.

In a subsequent study, Kriebel (1986) performed a more detailed calibration and verification of the model using several measured profiles from the Hurricane Eloise data set. In that study, one profile was selected and used to calibrate the numerical model. This profile, denoted R-41, was previously used by Hughes and Chiu (1981) to verify a small-sale physical model for dune erosion. This profile was also used by Vellinga (1986) to verify the Dutch dune erosion model for hurricane conditions. As a result, this profile has become a sort of calibration standard. From this, a value of the transport parameter, K, was found to be about 0.0045 ft^4/lb (8.75×10^{-6} m^4/N). This is larger than the value originally adopted from Moore (1982) but it provided results that were accurate to within about 25% when 20 other Hurricane Eloise profiles were simulated in detail. A comparison of the calibrated numerical model and the measured post-storm profile is shown in Figure 1.

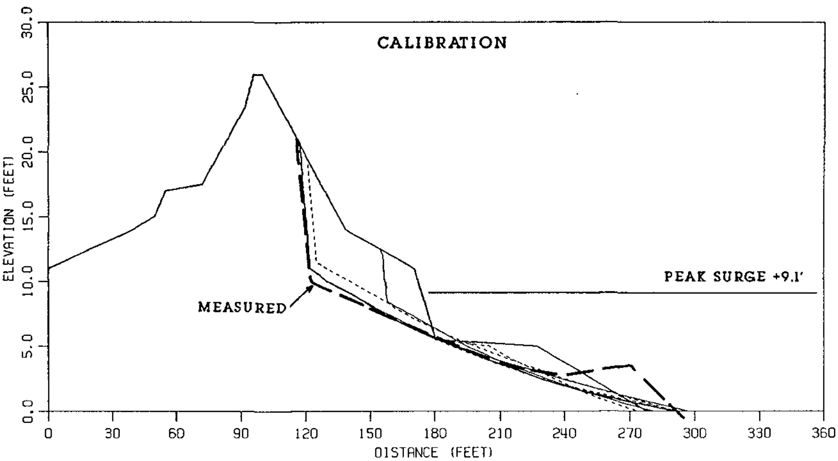


Figure 1. Example of predicted profile response for calibration profile R-41 from Hurricane Eloise data set.

MODEL REVISIONS

The revised numerical model uses the same governing equations to describe onshore-offshore transport and to solve for profile changes. The major revisions are in the initial profile description and in the onshore boundary conditions. In the original model, wave runup was not simulated and the entire dune face was required to erode while maintaining its initial slope. In the revised model, provisions for realistic wave runup limit are included along with a new method for estimating sediment transport rates on the beach face. This allows formation of a dune scarp along with flattened post-storm beach face slope.

Initial Profile Form

As shown in Figure 1, the initial profile is no longer limited to the two idealized forms used in the original model. Previously, the profile was defined only by the position of the dune crest, the slope of the dune face, the position of the berm, and the slope of the beach face. Dunes were assumed to be of infinite width which extended landward indefinitely at the elevation of the dune crest. In the revised model, the initial profile closely simulates a measured profile. Dunes of finite width may be simulated by specifying both a landward and a seaward position of each elevation contour to define the dune width at each elevation.

For narrow dunes, each elevation contour can then erode only until it reaches the landward contour location. Once erosion reaches this position at each elevation, no sand remains at or above that contour and the upper limit of the active profile is then taken at the next lower elevation contour. This routine also enables simulation of vertical and sloping seawalls when the wall location is used as the landward limit of each elevation contour. In these cases, once the eroding contour reaches the wall location, the upper limit of the active profile is again transferred to the next lower contour.

Runup Limit

Provisions are then made for input of a realistic runup limit to describe the upper limit of the active swash zone and to fix the transition from a flattened post-storm beach face to a near-vertical erosion scarp. This does not represent the true wave runup limit since runup for some waves in a random sea may reach above this elevation on the dune scarp. In some erosion models, such as the Dutch method of Vellinga (1983), the dune scarp is fixed at the peak storm surge level. This may be a good approximation in areas of high dunes where large amounts of sand are fed to the beach face by dune undermining and slumping. Most post-storm conditions in the U.S., however, show a distinct erosion scarp at an elevation above the peak surge level.

A more realistic upper limit on the eroded profile may be established from local field observations of previous storm events. For example, in the Hurricane Eloise data, the elevation of the dune scarp is about 2 feet (0.6 m) above the estimated peak still water level. This is below the elevation of debris lines surveyed after the storm and illustrates that the dune scarp usually forms below the maximum wave runup elevation.

For more general application, the elevation of the erosion scarp may be estimated by any of the available methods of predicting wave runup. One effective method is to estimate this elevation according to the Hunt formula

$$R = m_{*}(H_{rms}L_{o})^{1/2} \qquad (5)$$

where the deep water rms wave height is used along with an estimate of the equilibrium post-storm beach slope, m_{*}, to be discussed. Since the swash is saturated during severe storms, use of higher wave height descriptions, such as the significant wave height, seem to overestimate the dune scarp elevation. The above method seems to predict runup elevations that correspond closely with observed dune scarp locations and is of a comparable level of simplicity as the rest of the numerical model.

Post-Storm Beach and Dune Slopes

Methods are also required to describe the post-storm slopes of the beach face and dune face. The Vellinga model fixes the dune scarp at the peak surge level and assumes a 1:1 slope for the eroding dune face. This has recently been adopted in a similar erosion model for the National Flood Insurance Program described by Hallermeier and Rhodes (1988). This method works well for dune erosion in large wave tank tests but does not work as well for field conditions where a flattened post-storm beach face is usually evident below the dune scarp at an elevation above the peak surge level. In addition, most natural dunes are vegetated and display near-vertical post-storm slopes.

In the present model, any realistic post-storm dune scarp slope may be specified. For simulation of large wave tank tests, a slope of 1:1 is appropriate; however, for field conditions, slopes of 5 vertical to 1 horizontal are more reasonable. For the beach face slope , observations in the area of interest are usually the best guide when available. Lacking these, predictions can be made based on the observations of Sunamura (1984) where the beach slope was found to vary with sediment and wave conditions as

$$m_* = 0.12((gd_{50})^{1/2}T/H_{rms})^{1/2} \qquad (6)$$

It is found that offshore rms wave height works well in equation (6). However, Sunamura does not specify which wave height should be used in random waves and equation (6) was developed using observed breaker heights.

Sediment Transport on Beach Face

A major problem encountered in all numerical models of cross-shore beach response is that no simple descriptions are available of sediment transport rates in the swash region. This problem is symptomatic of a more fundamental problem: the lack of valid wave transformation models that describe wave conditions in the swash zone. As a result, existing numerical models for cross-shore transport must include ad hoc treatments of the sediment transport rate on the active beach face.

In the original model, sediment transport rates were calculated only in regions of finite water depth. The energy dissipation and the sediment transport rates were calculated by equations (3) and (4) for all points in the surf zone up to the last submerged depth. At this point, the transport value was determined and the transport distribution was then assumed to decrease linearly to zero at the runup limit. This leads, however, to uniform retreat of the beach face from equation (2) since the gradient in transport is the same at all elevations.

In the revised model, a simple algorithm is used to provide an estimate of sediment transport rates on the beach face based on geometrical arguments. Water level and wave conditions are established at each time step and two reference elevations are located. The depth h_* is first established at the transition depth where the equilibrium profile, with an $Ax^{2/3}$ form, is tangent to the equilibrium beach slope, m_*. The elevation h_u is then defined at the upper limit of the active profile, either at the runup limit or at the crest of the remnant dune if the dune is overtopped. Based on equation (3), the transport rate Q_* is then determined at the transition depth h_*. The volume of sand that must be eroded from the beach face between the elevation contours h_* and h_u over one time step is then $V_* = Q_* \Delta t$.

An estimate is then made of the potential eroded volume, V_p, between h_* and h_u. This so-called potential erosion prism is depicted in Figure 2 for three basic cases: two for beach face rotation and one for beach face translation. In Case I, the equilibrium slope is steeper than the existing slope. The erosion prism is then defined by passing the equilibrium slope through the runup limit, h_u, so that contours near h_* have the greatest erosion potential. In Case II, the equilibrium slope is milder than the existing slope. The erosion prism is defined by passing the slope m_* through the transition depth h_* so that contours near h_u have the greatest erosion potential. In Case III, the existing slope is in equilibrium. All elevation contours have the same erosion potential and the erosion prism is then defined by translating the beach slope landward until V_p equals V_*.

In general, the potential volume V_p defined in Cases I and II does not equal the demand volume V_*. When the potential volume is too large, only the fraction V_*/V_p is actually eroded over the time step. When the potential volume is too small, the additional volume must then be supplied by translating the equilibrium slope m_* landward. In this way combinations of Cases I and III and Cases II and III are used to obtain the final potential volume V_p.

The estimated distribution of sediment transport on the beach face is finally established according to the fraction of the potential volume that may be eroded from above each elevation contour. Denoting the potential volume above contour n as V_n, the transport rate at elevation contour n is estimated as

$$Q_n = Q_* \, (V_n/V_p) \tag{7}$$

For the cases depicted in Figure 2, this gives the transport distributions depicted in Figure 3.

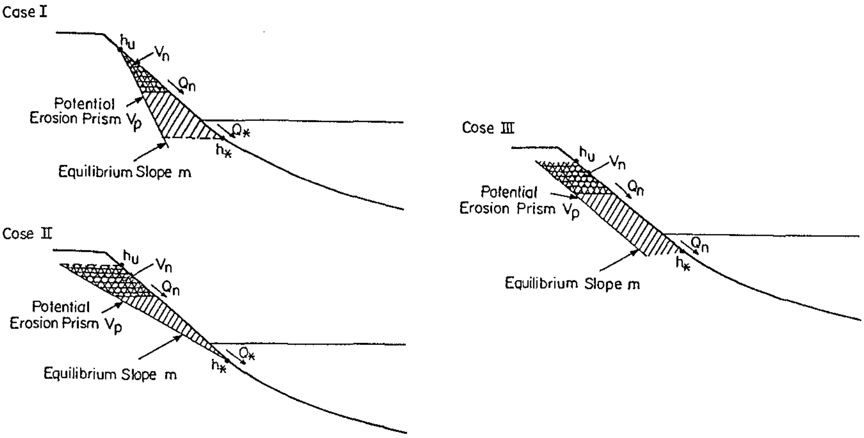


Figure 2. Illustration of potential erosion prism for fundamental cases of beach face rotation and translation.

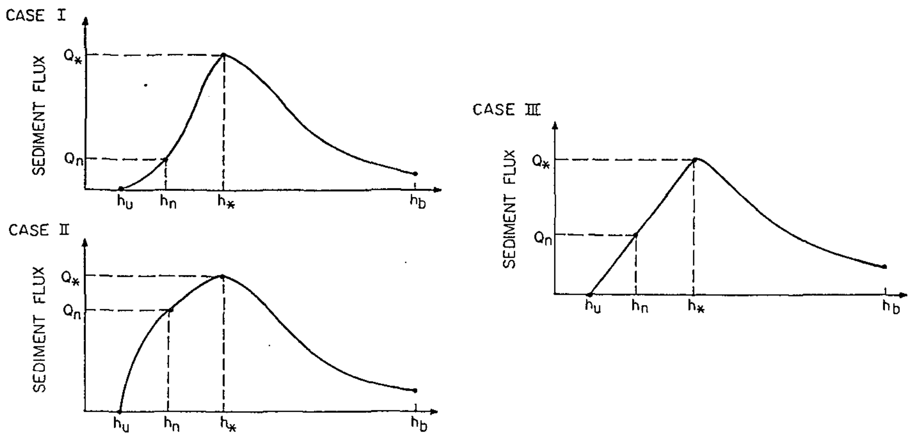


Figure 3. Illustration of sediment transport distributions for example cases shown in Figure 2.

For Case I, the beach slope steepens since the transport distribution is concave with the largest gradients near h_*. For Case II, the beach face must flatten since the transport distribution is convex with the largest gradients near the runup limit h_u. For Case III, the beach face maintains its initial slope as it erodes since the transport distribution is linear with uniform gradients at all elevations. With this method, the beach face evolves toward the specified equilibrium slope while the submerged profile evolves toward the $Ax^{2/3}$ form. An example of the computed slope evolution is shown in Figure 4 for one of Saville's (1957) large wave tank tests. In this case, the equilibrium slope is steeper than the original 1:15 slope and slope steepening is simulated by the above method.

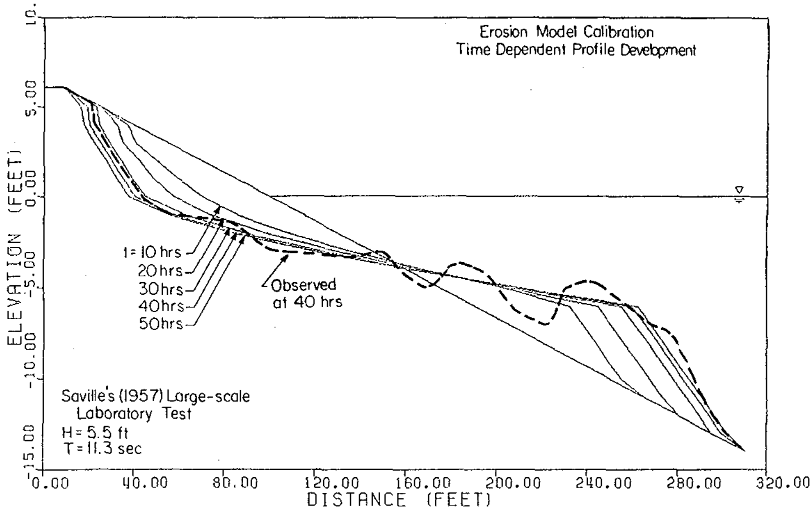


Figure 4. Example of slope steepening introduced by the potential erosion prism method.

Examples of Model Application

In order to validate the revised model, several large wave tank results of dune erosion using random waves were simulated. These included tests described by Vellinga (1986) as well as tests described by Dette and Uliczka (1987). In each case, the initial profile form, water level, wave conditions, and sand grain size were obtained from the references cited. The A parameter for the equilibrium profile form was obtained from Dean (1987) based on the median grain size. The equilibrium beach slope, m_*, was estimated using equation (6). A post-storm dune slope of 1:1 was assumed and the elevation of the dune scarp was estimated from equation (5). The offshore breaking depth, forming the offshore limit to sediment deposition, was adopted as 1.06 times the rms wave height, in accordance with observations by Vellinga (1983).

One example of these simulations is shown in Figure 5. Numerical results are shown for simulation times of 0.1, 0.3, 1, 3, 6, and 10 hours while the measured profile obtained after 10 hours in the Delta Flume is also shown. For this case, the dune scarp elevation and horizontal location are slightly underpredicted but, in general, the scarp formation and the eroded volume are predicted to within about 10% from their measured values. Similar results were then obtained from the other tests with numerical results generally being within about 10 to 20 percent of the measured values.

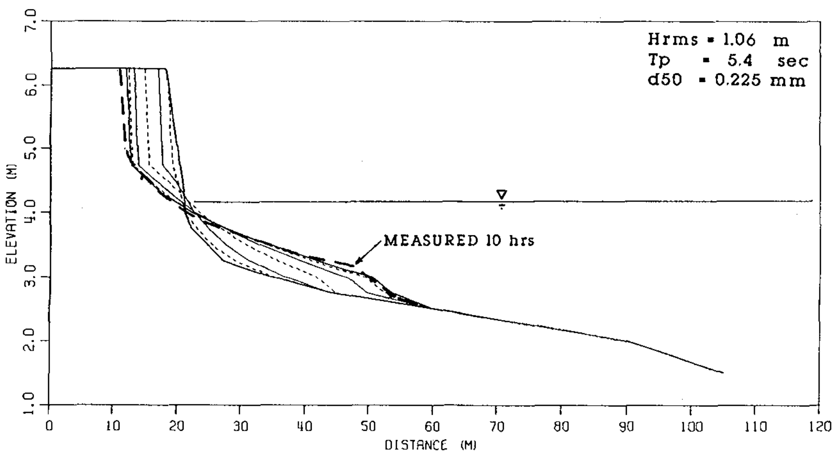


Figure 5. Comparison of erosion simulation to measured profile response for test #2 of Vellinga (1986).

A similar comparison is shown in Figure 6 for the case of a sand beach backed by a sloping dike tested by Dette (personal communication). The predicted profiles are shown at times of 0.25, 0.5, 1.25, 2.75, and 4.0 hours and are compared to the measured profile after about 3 hours. In this case, the final profile form at the base of the dike is predicted reasonably well. Once the upper contours eroded back to the wall location, the upper limit of the active profile is transferred to the next lower contours and it is found that these erode faster for a time until they approach equilibrium.

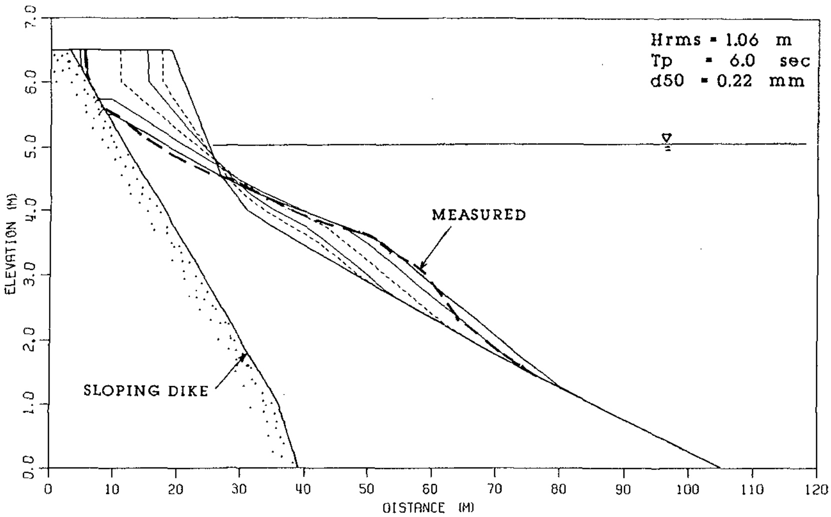


Figure 6. Example of profile backed by seawall tested by Dette (personal communication).

In Figure 7, field conditions documenting the complete erosion of a narrow dune are simulated, based on data presented by Chiu and Dean (1986) for Hurricane Frederic on the Alabama coast. This storm was similar to Hurricane Eloise in that the storm duration was very short. However, Hurricane Frederic was more severe in that the peak surge elevation was higher and since the storm struck an area with relatively low dunes that were overtopped. As shown in Figure 7, the numerical model predicts the formation of a dune scarp for the first profile, 3.2 hours before the peak surge. On the next profile, 1.6 hours before the peak surge, wave runup overtopped the remnant dune. On the third profile, at the time of the peak surge, the dune was submerged and was then quickly flattened afterward.

At present, the numerical model simulates only offshore transport at the crest of the remnant dune and does not simulate landward transport of sand due to overwash. Trial calculations with an upper boundary condition that includes overwash transport gave a faster planing of the remnant dune crest and results that agree more closely with the measured profile. However, more accurate data is needed to verify this algorithm. With the present approximation, reasonably realistic estimates of the time at which the dune is breached can be obtained.

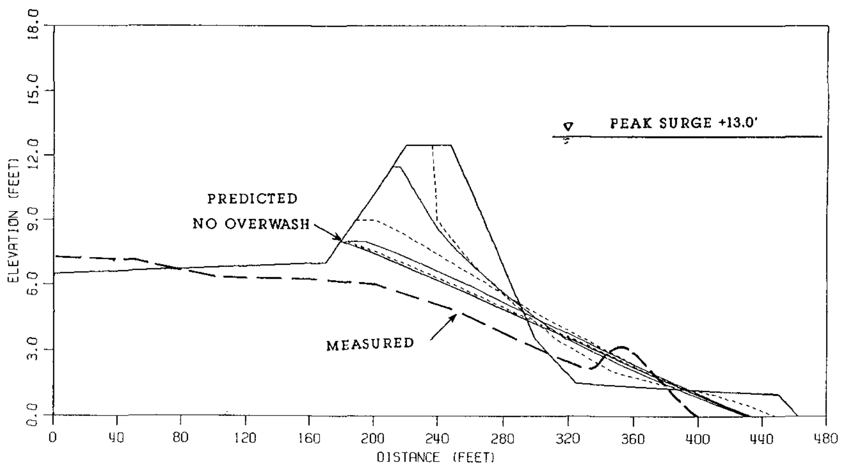
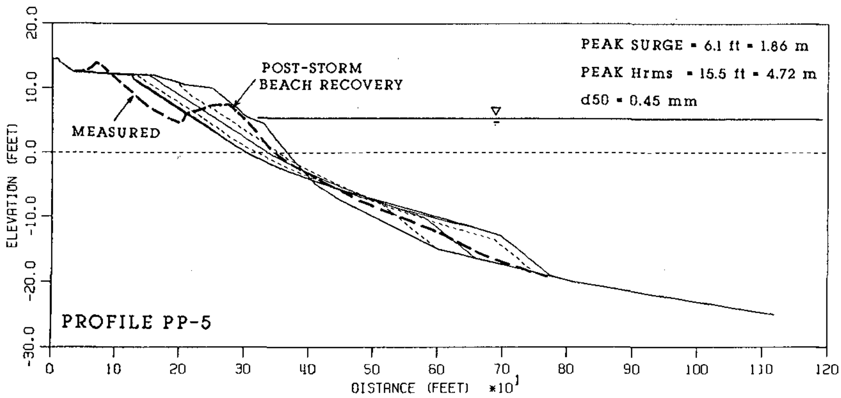


Figure 7. Example of erosion of narrow dune during Hurricane Frederic as reported by Chiu and Dean (1986).

As a final example, Figure 9 shows results from the simulation of a long-duration winter storm from the coast of New Jersey. In this case, data were provided to the author by Jeff Gebert of the Philadelphia District of the Corps of Engineers. A total of 17 profiles were measured out to a depth of about 10 meters 1 to 2 days before the storm and were then remeasured just 3 to 4 days after the storm. Wave and water level conditions were both measured during the duration of the storm. This data set probably constitutes the most well documented storm erosion case on the U.S. East coast.

This condition is also interesting since: (1) the median grain size (from the beach face) is much larger than any other condition previously simulated, (2) the storm lasted for more than 2 days but included a peak surge elevation of only 6.1 feet (1.86 meters), and (3) the eroded volumes are very large, on the order of 1100 ft^3/ft (100 m^3/m). Results in Figure 9 are shown since they represent examples of model under and overprediction, in this case occurring on adjacent profiles located just 175 meters apart. Some post-storm recovery had occurred by the time of the post-storm survey and the presence of beach cusps may explain some of the differences observed on the beach face in the two profiles. These cases demonstrate, however, that the numerical model gives reasonable results for long-duration storm events.



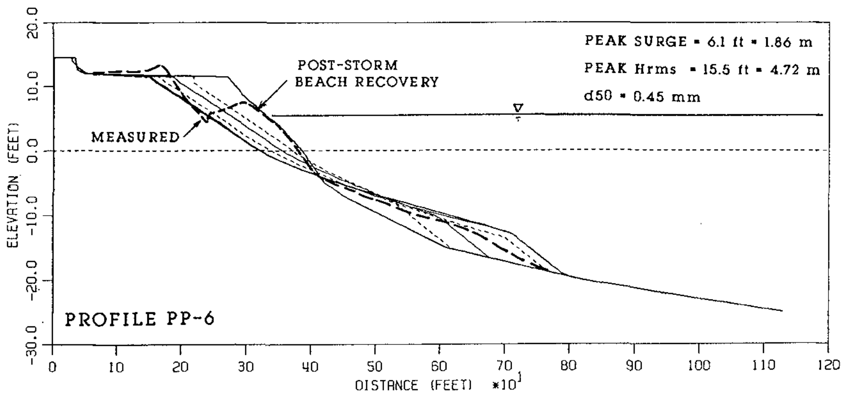


Figure 9. Examples of storm simulation for March 1984 storm at Pt. Pleasant, New Jersey.

CONCLUSIONS

Numerical algorithms may be readily developed to handle most dune erosion conditions to a first level of approximation which retains an overall level of simplicity in terms of required parameters and numerical code. For example, a simple method has been presented for estimating sediment transport rates on the beach face. Such numerical algorithms may then be incorporated into other macroscopic profile response models to enhance their applicability to a broad range of dune geometries. However, other more physically-based methods of predicting wave transformation and sediment transport on the beach face are needed, along with new lab and field data for model verification.

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