## CHAPTER 180

# Development of a Dune Erosion Model using SUPERTANK Data

Margery F. Overton[1]
John S. Fisher[2]
Kyu-Nam Hwang[3]

## Abstract

A model predicting dune erosion under storm conditions has been developed using data from SUPERTANK laboratory experiments. In this model, the swash approach is applied with the basic assumption that the volume eroded from the dune is a function of the swash force acting on the dune. The swash force is characterized with swash parameters, specifically the swash height, the swash velocity and the swash period. For given storm conditions, the model predicts wave height variation across-shore, swash height variation on the beach face, swash velocity, swash period, swash forces and finally volume eroded at the dune. Predictions of swash parameters and dune erosion are compared with measurements from SUPERTANK laboratory experiments.

## Introduction

A lot of effort has been made to develop a prediction model for dune erosion by storm events and the resulting beach profile. An extensive research program for the process of dune erosion due to wave impact was started by Fisher and Overton (1984). Their approach for the process of dune erosion is based on the interaction of the wave swash and the dune. This approach treats the dune erosion phenomenon as a time-dependent process in which a series of successive uprushes attack the dune face. Each individual uprush erodes a finite volume of sand which in turn is deposited on the eroding beach.

Currently, the most important achievement in the development of a dune erosion model due to wave impact is the experimental observation of the linear

[1] Associate Professor, Department of Civil Engineering, North Carolina State University, Box 7908, Raleigh, NC 27695-7908.
[2] Professor, Dept. of Civil Engineering, NCSU.
[3] Graduate Research Assistant, Dept. of Civil Engineering, NCSU.

relationship between swash force and dune erosion. This linear relationship has been confirmed through field measurements (Fisher et al., 1986) and laboratory experiments (Overton et al., 1988). Therefore, it is possible to predict the dune erosion from this relationship if the swash force is known for the given storm conditions. However, limited knowledge of swash parameters, which are identified as swash height, swash velocity and swash period, has discouraged the development of a quantitatively (or even qualitatively) reliable predictive model.

It is therefore highly instructive to understand qualitatively the hydrodynamics of the swash zone in terms of waves generated by storms outside the surf zone. These waves commonly serve as an input for the prediction of transformed waves in the surf zone. For this purpose, a set of experiments designed to simulate dune erosion under storm conditions at prototype scale was conducted in the large wave tank at the O. H. Hinsdale Wave Research Laboratory, Oregon State University as part of SUPERTANK Laboratory Data Collection Project. Through the analysis of SUPERTANK laboratory data for the swash parameters, an attempt is made in this study to produce useful information regarding hydrodynamics in the swash zone, and to develop a predictive model for dune erosion by wave impact.

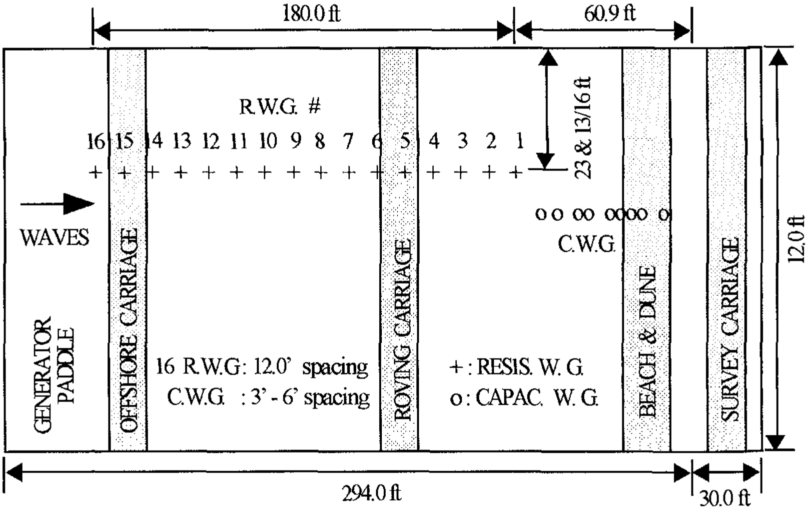


Figure 1. Configuration of flume and location of wave gages.

**Laboratory Experiments**

The experiments were designed to simulate dune erosion under storm conditions at prototype scale. Flume configurations with the locations of wave gages are shown in Figure 1. A dune of 5 ft height was constructed with fine sands of median grain sizes, $d_{50}$, of 0.23 mm. A vibrating compactor was used to consolidate the artificial dune. Sixteen resistance wave gages designed at OSU (Dibble and Sollitt, 1989) were used to obtain wave data across-shore and ten capacitance type wave gages were placed on the beach in front of the dune to collect swash data. The OSU data acquisition system sampled the wave gages at a rate of 16 Hz. The pre- and post-test beach and dune profile were surveyed. Additionally, dune position was documented by a 35 mm camera before, during and after each experiment. Each photograph of the dune included the profile of the dune face and a 2 ft by 2 ft standard grid to determine scale.

Thirteen experiments were successfully conducted. The design conditions of each test are given in Table 1. The design wave heights, $H$, ranged from 1.640 ft to 2.625 ft while the wave periods, $T$, ranged from 3 sec to 6 sec. The duration of the tests, $T_d$, ranged from 10 minutes to 30 minutes and the water level (WL) varied from 9.5 ft to 11.0 ft. The water level is defined as the distance from the original bottom of the flume to the still water surface.

| Test # | $T_d$ (min) | $T$ (sec) | $H$ (ft) | WL (ft) | Test # | $T_d$ (min) | $T$ (sec) | $H$ (ft) | WL (ft) |
|---|---|---|---|---|---|---|---|---|---|
| **1** | 10 | 3.0 | 2.625 | 9.5 | **8** | 20 | 3.0 | 2.297 | 10.5 |
| **2** | 20 | 3.0 | 2.625 | 9.5 | **9** | 20 | 3.0 | 2.297 | 10.5 |
| **3** | 30 | 4.5 | 2.625 | 9.5 | **10** | 20 | 4.5 | 2.297 | 10.5 |
| **4** | 30 | 6.0 | 2.625 | 9.5 | **11** | 20 | 4.5 | 2.297 | 10.5 |
| **5** | 30 | 4.5 | 2.297 | 10.5 | **12** | 20 | 4.5 | 2.297 | 10.5 |
| **6** | 30 | 6.0 | 2.297 | 9.5 | **13** | 20 | 6.0 | 1.640 | 11.0 |
| **7** | 30 | 3.0 | 1.640 | 9.5 | | | | | |

Table 1. List of Experimental Design Parameters.

Using a standard Fourier Transform, frequency domain analyses were performed on the SUPERTANK hydrodynamic data collected in the prebreaking and breaking zone. The wave parameters calculated from frequency domain analyses are *rms* and significant wave height. Both time domain analyses and frequency domain analyses were performed on the time history of the water surface variation in the swash zone. The swash parameters calculated from time domain analyses are mean value of swash height, swash peak height, swash velocity, swash period. The representative swash heights calculated from the power spectra are *rms* and significant swash height.

Typical features of an individual swash recorded during the experiment are given in Figure 2. Height of swash is defined as the difference between the background height and the height of the plateau before the start of the backwash. The velocity of the leading edge of the swash (or swash velocity, $V_{sw}$) is determined by identifying the time at which the swash hits the first and the second probes on the beach. The swash period $T_{sw}$ of an individual swash is defined as the time between the initial swash hits.

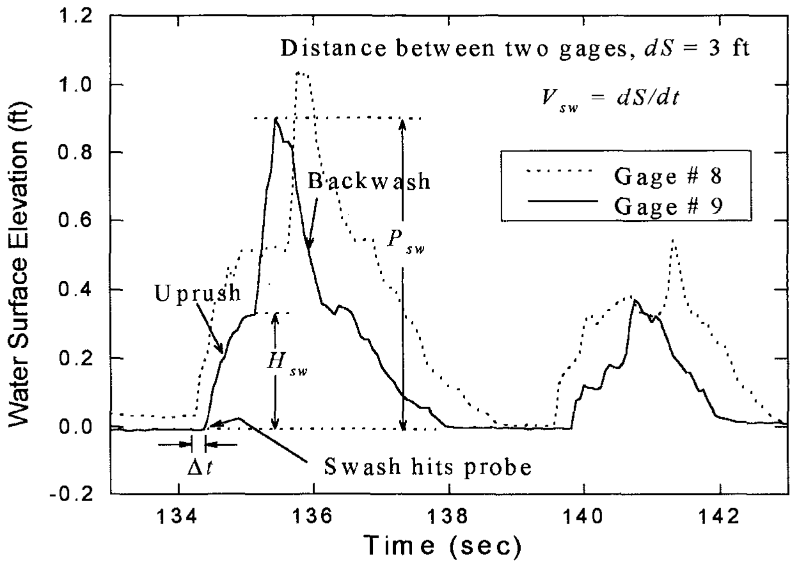


Figure 2. Definition of swash parameters.

Survey data was used to determine the dune and beach profiles for each test. A polynomial smoothing method was applied to the survey data to obtain the depth data equally spaced in the horizontal direction. Specific volume eroded at the dune, $Q_e$, was determined from the before and after profiles of the dune face as recorded on 35 mm film, and checked with survey profiles of the beach and dune. In order to differentiate between beach erosion and dune erosion, the initial face of the dune was used to define the seaward extent of the dune.

An individual swash force acting on the dune is defined as

$$F_{swi} = \rho V_{swi}^{\ 2} H_{swi} \tag{1}$$

where $\rho$ is the density of the water, $H_{swi}$ is an individual swash height and $V_{swi}$ is the swash velocity. While quantifying the force for an individual swash is possible using (1), it is not always possible to measure the amount eroded due to that loading. One possible way is to use the "summing-up" method by Overton et al. (1988), in which the summation of the force in a given interval of time versus the volume of eroded in the same time interval becomes the quantity evaluated. Each individual swash force was determined by (1) and summed up to obtain the total swash force, $F_{sw}$, for a given duration of time. Linearity between dune erosion and swash force was examined. Figure 3 shows the estimated data and the best linear fit line with a $R$-squared value of 0.90. An apparent linear relationship exists between dune erosion and swash force.

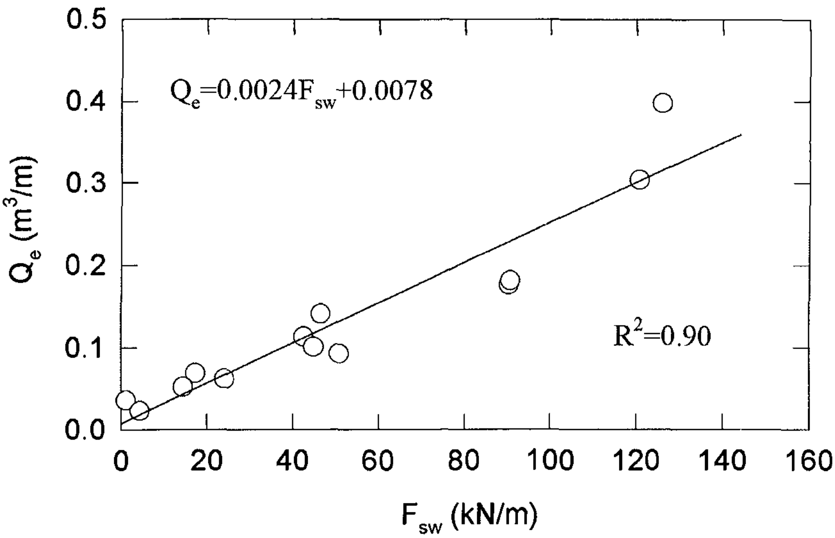


Figure 3. Linearity of dune erosion as a function of swash force.

**Modeling of Swash Parameters**

Swash parameters required for the prediction of dune erosion are the swash height, swash velocity, and swash period. In the current stage of modeling dune erosion due to wave impact, individual swashes (or waves) are not considered. Instead, statistically representative swash parameters (e.g., mean, rms and significant swash) are used to develop the prediction model.

A beach profile in the cross-shore direction is divided into three regions: the prebreaking zone, surf zone, and swash zone. In order to predict the swash height in the swash zone with a given condition in deep water, it is necessary to predict the cross-shore variation of wave height in the prebreaking and surf zone. Linear wave theory has been used to determine wave height across-shore from deep water to the initial break point of waves. Wave height transformation in the surf zone has been calculated by applying the breaking wave dissipation model by Thieke and Sobey (1990).

Modeling of Wave Height

Several models have been developed to predict surf zone wave height variation, based upon the conservation of energy equation (Battjes and Janssen; 1978, Dally, et al.; 1985, and Stive; 1984). The steady-state, depth-integrated equation governing the energy balance for waves propagating directly towards shore is simply

$$\frac{\partial F}{\partial x} = -D \tag{2}$$

where $F$ is the wave energy flux, $x$ is the distance along the propagation path, and $D$ is the rate of energy dissipation per unit plan area due to breaking.

Thieke and Sobey (1990) established a form of a predictive equation for the breaking wave dissipation as

$$D = f_{bw}\omega E \tag{3}$$

where $f_{bw}$ is a dimensionless breaking wave dissipation coefficient, $\omega$ is the spectral peak frequency and $E$ is the wave energy. Adopting a simple direct partition estimator yields an expression for $f_{bw}$:

$$f_{bw} = \alpha\left(1 + \frac{H_m^2}{H_{rms}^2}\right)\exp\left(-\frac{H_m^2}{H_{rms}^2}\right) \tag{4}$$

where the coefficient $\alpha$ is of order $1/\pi$ (or perhaps $H_b/(\pi h)$), $H_m$, a local limiting wave height, is order of $0.83h$ and $H_{rms}$ is the root-mean-square wave height.

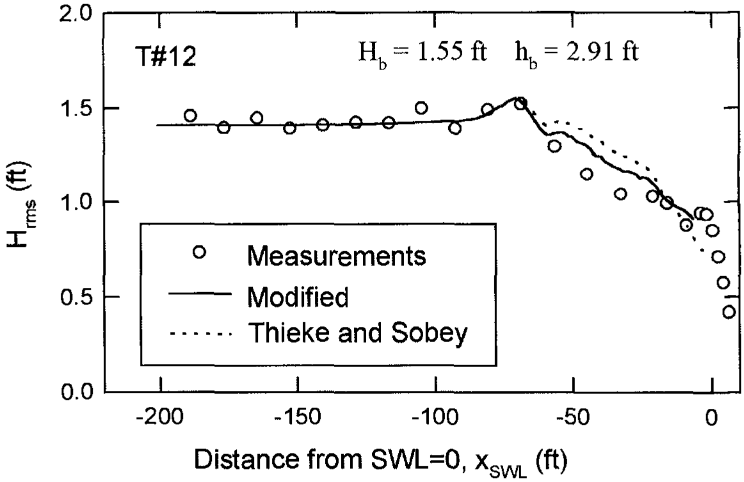


Figure 4. Measured and predicted wave height variation in the prebreaking and breaking zone.

Predictions by Thieke's model for wave height variation in the surf zone are shown in Figure 4 as a dotted line. The measured *rms* wave height has been computed by $2\sqrt{2}\sigma$ ($\sigma$ is a spectral estimate of the standard deviation of the water surface). While the trend predicted by Thieke's model is physically reasonable, the model underpredicts significantly the wave height near the swash zone. In order to obtain more accurate predictions of the wave height near the swash zone, a modification to Thieke's model has been made to decrease the breaking wave dissipation near the swash zone. Calibrating the predicted wave heights (by Thieke's model) to the measurements, the quantity of the coefficient $\alpha$ in (4) was computed for all 13 tests. By scaling arguments it can be shown that Thieke's model is improved when the coefficient $\alpha$ is related to $H_b$, $h_b$, and $H_o$ by the following expression :

$$\alpha = 0.8\frac{H_o}{H_b} + \left(23.06\frac{H_b}{h_b} - 5.79\right)^{-1} \frac{H_b}{H_o} \tag{5}$$

where $H_b$, $h_b$, and $H_o$ are the initial breaking wave height, the corresponding depth, and deepwater wave height, respectively. Note that prediction of wave height in the middle of the surf zone (beach profile section between -50 and -30 ft of xSWL) was sacrificed to obtain the best prediction near the swash region. It was necessary since the wave height predicted at the end of the surf zone is used as an initial value for the prediction of swash height in the swash zone. The model predictions with the modified coefficient $\alpha$ are shown as a solid line in Figure 4. Near the swash zone, agreement between predicted and measured wave height is excellent.

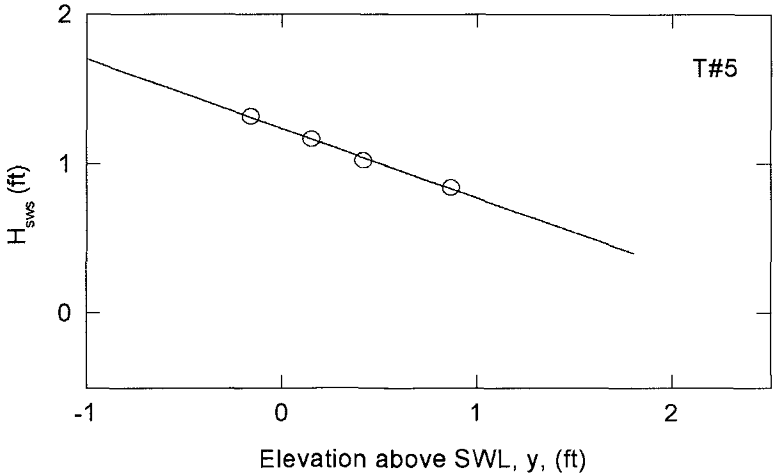


Figure 5. Significant swash height variation on a beach face for Test #5.

Modeling of Swash Height

Since the swash phenomena in nature is so complicated, no attempt has been made to express, in a simple manner, the swash height variation on a beach face. Figure 5 shows the measured significant swash height ($H_{sws}$) variation versus beach face elevation ($y$) for Test #5. The elevation of beach face represents the positive elevation above the still water level (SWL) and the negative elevation below it. The most important experimental observation is that the swash height decreases linearly with beach face elevation, which is apparent in all 13 tests. This linearity of the swash height on the beach face plays a key role in establishing a model for swash height variation.

Applying boundary conditions of i) $H_{sws} = 0$ at $y = y_{\max}$ and ii) $H_{sws} = H_{swso}$ at $y = 0$, this linearity yields a prediction model for the swash height :

$$1 - \frac{H_{sws}}{H_{swso}} = \frac{y}{y_{\max}} \tag{6}$$

where $H_{swso}$ represents a significant swash height at $y$=0 and $y_{\max}$ is the beach face elevation where a significant swash height becomes zero.

Note that if $y_{max}$ is known for a given deep water wave condition, (6) becomes an initial value problem and can be used directly to compute the swash height for a given elevation. In order to quantify $y_{max}$ for each test, the left side of (6) was computed with the measured swash height and plotted with $y$. The best linear fit lines (crossing the origin) to the measured data allow determination of $y_{\max}$ for each test. The significant swash height at $y$=0, $H_{swso}$, for each test has been determined by the interpolation of the measured swash height.

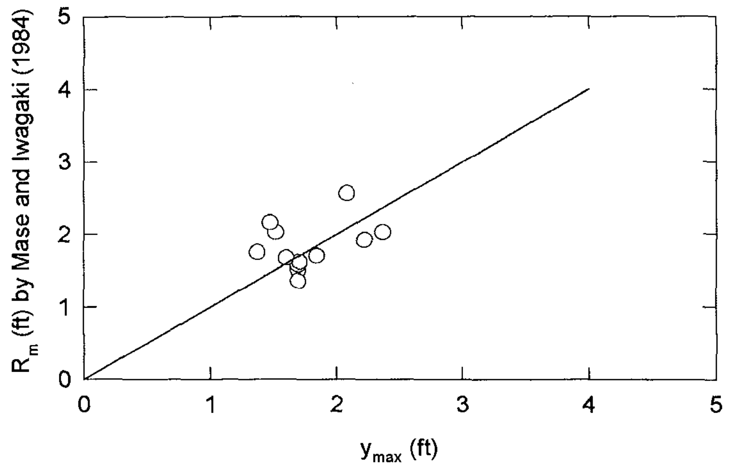


Figure 6. Comparison of $y_{max}$ with the mean runup height by Mase et al. (1984).

Since $y_{\max}$ can be physically interpreted as a representative runup height for irregular waves climbing on the beach, it would be valuable to examine $y_{\max}$ with respect to the existing models for runup heights. Mean run-up heights for each test were computed from the runup height equation proposed by Mase and Iwagaki (1984). The comparisons between $y_{\max}$ and the computed runup heights are shown in Figure 6. It is noticed that $y_{max}$ appears to matches roughly with mean runup heights $R_m$ by Mase et. al (1984), as $y_{max}$ deviate by at most a factor of 2 from $R_m$.

The swash height variation in the swash zone was predicted using (6). The comparisons between the measured and the predicted swash height variation in the swash zone for Test # 5 are shown in Figure 7. The solid line represents the predicted swash height variation using $R_m$ computed from runup equation by Mase et. al (1984).

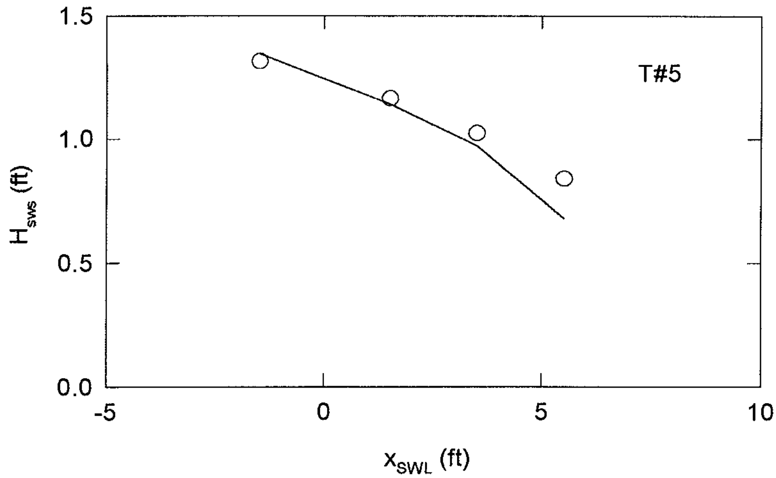


Figure 7. Comparison between predicted and measured swash heights for Test #5.

Swash Velocity Model

In order to develop a prediction model for swash velocity, it is assumed that it is possible to idealize the water particle as a solid particle which retains its identity. Thus, a particle of swash height, $H_{sw}$, is considered to move up and down the beachface as a solid particle would. If the normally incident waves are considered, a force balance implies

$$m\frac{dV_{sw}}{dt} = -mg\sin\theta - \frac{f}{8}\frac{m}{H_{sw}}|V_{sw}|V_{sw} \tag{7}$$

where $m$ is a mass of the water particle, $V_{sw}$ is a swash velocity, $g$ is the gravitational acceleration, $\theta$ is the beach slope and $f$ is a friction factor. For simplicity, a frictionless planar beach is assumed. Eliminating common terms and applying initial conditions of $V_{sw} = V_{swo}$ at $x=y=0$ (where $x$ is the distance in the water particle translation direction from the location of $SWL=0$), simple integration of this equation yields

$$V_{sw} = \sqrt{2g(y_{\max} - y)} \tag{8}$$

where $y$ is the elevation positive from SWL.

The swash velocity for each test has been predict from (8). The comparisons between the measured and the predicted velocity are given in Figure 8. Note that the predicted velocity matches well with the measured significant velocity.

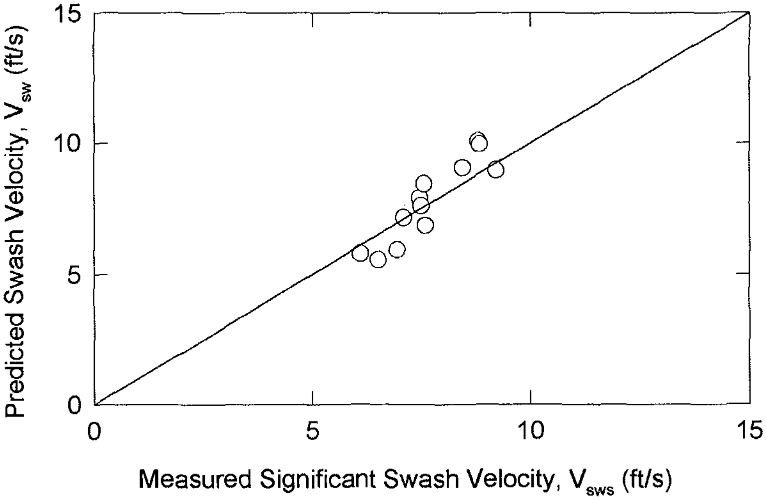


Figure 8. Comparison of the predicted swash velocity to the measured swash velocity.

Modeling of Swash Period

In order to develop a prediction model for swash period, a possible simple method is to apply a model which predicts the probability of wave overtopping for offshore structures. Since the probability of runup can be expressed as $T_{swo}/T_{sw}$, the runup prediction model becomes

$$T_{sw} = T_{swo} \exp\left[\left(\frac{y}{R_{rms}}\right)^2\right] \tag{9}$$

assuming that the runup height on natural beaches has a Rayleigh distribution. In (9), $T_{swo}$, and $T_{sw}$ are the initial swash period at $y$=0, and the swash period at any elevation of $y$, respectively, and $R_{rms}$ is the *rms* value of runup height.

Note that in order to apply (9) for the prediction of swash period, it is necessary to express both $T_{swo}$ and $R_{rms}$ in terms of known deepwater wave conditions or swash variables. It is possible to express $T_{swo}$ with $T_o$ using the laboratory data by Mase and Iwagaki (1984). They indicated that the ratio of the number of deep water waves to the number of runup waves, $N/N_o$ (or $T_o/T_{swo}$), varies nonlinearly with the deep water wave condition, expressed as the Iribarren number. Fitting a second order polynomial to their experimental data yields

$$\alpha = \frac{T_o}{T_{swo}} = 0.69\xi^{(0.42-0.08\ln\xi)} \tag{10}$$

where $T_o$ is the deepwater wave height and $\xi$ is the Iribarren number (or surf similarity parameter). From the analysis of the laboratory measurements, Hwang (1995) also gives a linear relationship between $R_{rms}$ and $y_{max}$ :

$$y_{\max} = 1.65R_{rms} \tag{11}$$

From (10) and (11), the swash period is given as

$$T_{sw} = \frac{T_o}{\alpha}\exp\left[\left(\frac{1.65y}{y_{\max}}\right)^2\right] \tag{12}$$

A comparison between the predictions and the measurements for the swash period is shown in Figure 9. The predictions for the swash period are in good agreement with the measurements.

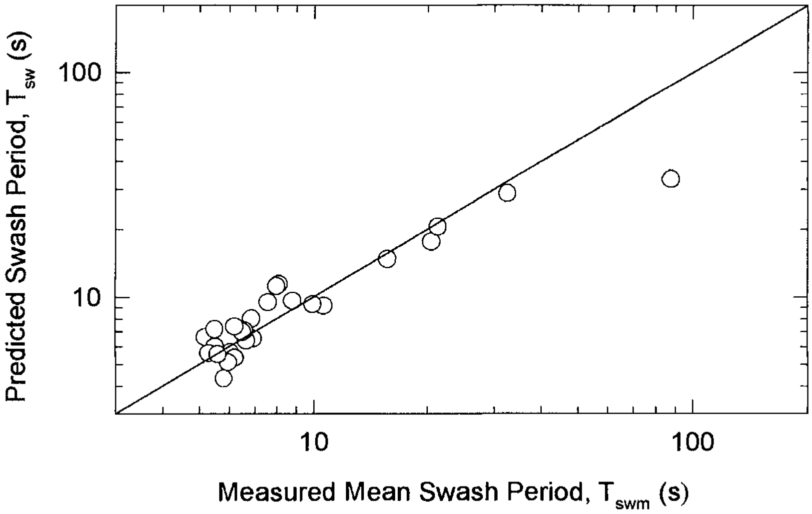


Figure 9. Comparison of the predicted to the measured swash period.

Modeling of Swash Force

Previously, the summing-up method has been used to relate the swash force to the volume eroded at the dune. However, applying this method directly to the prediction model for dune erosion is computationally intensive since each swash has to be computed and summed up for each time step (usually 20 minutes). An alternative approach is to use statistically representative swash parameters, such as mean, *rms* and significant values. As an example, a swash force by mean parameters may be defined as

$$F_{swm} = \rho \frac{T_d}{T_{swm}} V_{swm}^{\ 2} H_{swm} \qquad (13)$$

where subscript $m$ represent the mean values of the swash height, the swash velocity, and the swash period. Note that the ratio $T_d/T_{swm}$ in (13), which represents the number of swash hit at the dune face, is introduced to scale the total swash force for a given duration of test.

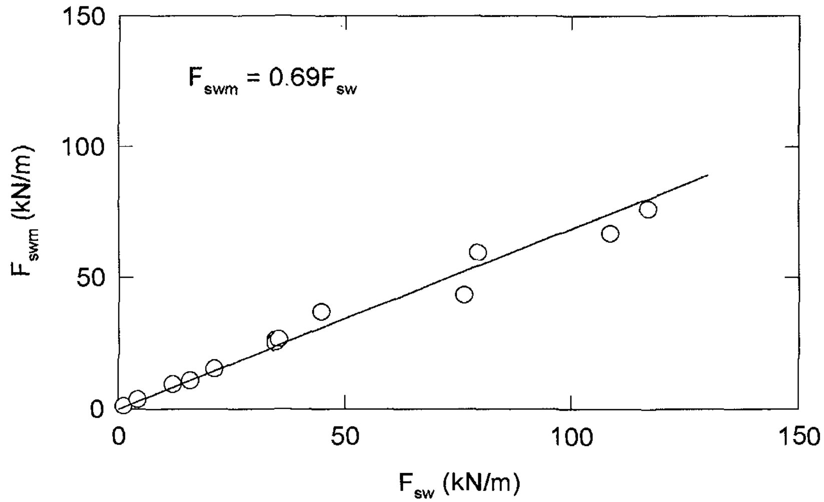


Figure 10. Relationship between $F_{swm}$ and $F_{sw}$.

The swash force by mean parameters was computed with the measured mean swash parameters for each test. Comparisons of the swash force using (13) with total swash force ($F_{sw}$) obtained by summing-up method are shown in Figure 10. It is interesting to notice that swash force defined by mean swash parameters is linearly related with the swash force by the summing-up method. The linear relationship obtained by the best fit line is

$$F_{swm} = 0.69 F_{sw} \qquad (14)$$

## Predictive Model for Dune Erosion

The dune erosion model predicts the volume eroded at the dune due to wave impact. The model consists of an input data routine, prebreaking zone wave height routine, surf zone wave height routine, swash zone hydrodynamics routine, dune erosion routine, and an output routine. As initial input data, the model requires the deepwater wave conditions and initial beach and dune profile data. Linear wave theory is used to determine the wave height from deepwater or a specified water depth offshore to the breaking point. Shoreward of the breaking point, a modified form of Sobey's prediction model is used to compute the wave height. The swash zone hydrodynamics routine computes each statistically representative swash height, swash velocity, and swash period. Once the swash parameters are determined, the corresponding swash force is computed and used to calculate the volume eroded at the dune.

In order to determine the wave heights across-shore, the model uses an explicit solution scheme in which quantities known at a specific grid point are used to determine corresponding quantities at the next grid point. Propagation of individual waves is not described by the model.

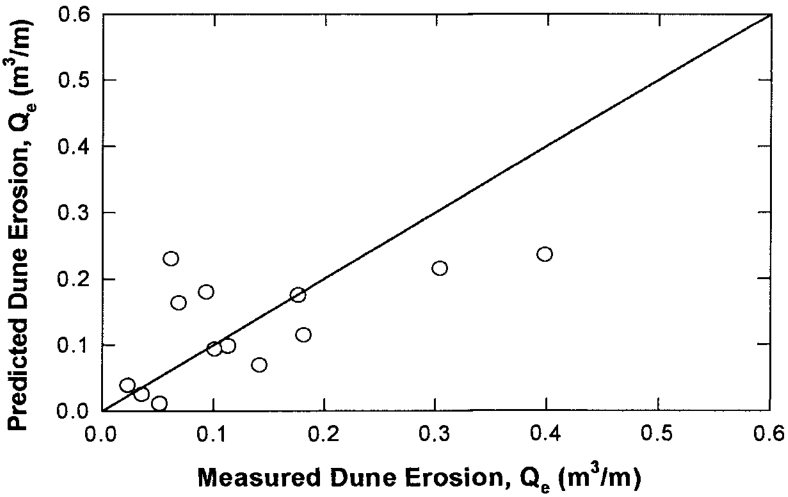


Figure 11. Comparison of predicted dune erosion to the measured dune erosion using predicted $R_m$ from runup equation.

Dune erosion was simulated for all 13 tests using the data from SUPERTANK laboratory experiments. Data used for each prediction were the significant wave height at Gage #14, peak spectral wave period at Gage #14, mean wave period at Gage #14, beach and dune profile, test duration, and dune toe location. Assuming that $y_{max}$ can be replaced by runup height, the runup height equation proposed by Mase and Iwagaki (1984) was used for the computation of $y_{max}$ which was required for the prediction of all swash parameters (swash height, swash velocity and swash period). Comparisons of model predicted dune erosions with measurements for all 13 tests are shown in Figure 11. It is easily noticed that the prediction of dune erosion by model is not successful. The model predictions deviate by as much as a factor of 4 from the measured dune erosion.

Since the runup height equation has been used for the prediction of $y_{max}$, a slight modification to the model was made to check the effect of the runup height on the prediction of dune erosion. Instead of calculating the runup height and using it as $y_{max}$, the measured $y_{max}$ was used for the simulation of swash force and dune erosion for each test. Predictions of dune erosion using the measured $y_{max}$ are shown in Figure 12 and compared with the measured dune erosion. It is obvious that predictions are much improved, as the model predictions deviate by at most a factor of 2 from the measured values.

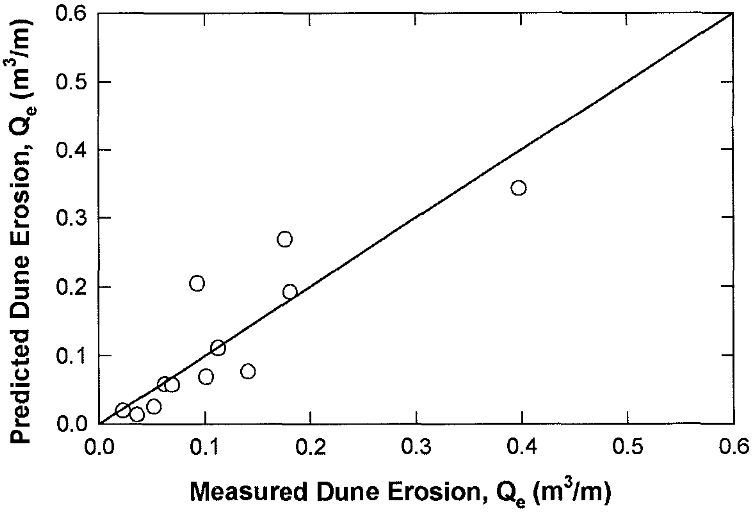


Figure 12. Comparison of predicted dune erosion to the measured dune erosion using the measured $y_{max}$.

Clearly, $y_{max}$ is a significant factor and plays a important role in the prediction of dune erosion. Consequently, it is concluded that quantitatively good prediction for dune erosion can be obtained by improving the ability of prediction of $y_{max}$.

## Conclusions

A simulation model has been developed using SUPERTANK experimental data to predict dune erosion due to wave impact. The analysis of the laboratory data confirmed an apparent linearity between swash force and dune erosion. With a modification of Sobey's model, predictions of wave height variation in the surf zone were improved, especially near the swash zone. Swash height, swash velocity, and swash period predicted by the model agreed well with the laboratory measurements. However, the model predicted dune erosion with limited success. An uncertainty in the value of $y_{max}$ is the primary cause which led to the failure of the prediction of dune erosion. The results indicate that improvement in the dune erosion model will depends upon more reliable estimates of runup height.

**References**

Battjes, J. A., and Janssen, J. P. F. M. 1978. "Energy Loss and Set-up Due to Breaking of Random Waves", *Proceedings of the 16th Coastal Engineering Conference*, ASCE, Vol. 1, pp 569-587.

Dally, W. R., and Dean, R. G., and Dalrymple, R. A. 1985. "Wave Height Variation Across Beaches of Arbitrary Profiles", *Journal of Geophysical Research*, Vol. 90, No. 6, pp 11917-11927.

Dibble, T. L., and Sollitt, C. K. 1989. "New Designs for Acoustic and Resistive Wave Profiles", *Proceedings*, Workshop on Instrumentation for Hydraulic Laboratories, IAHR.

Fisher, J. S., and Overton, M. F. 1984. "Numerical Model for Dune Erosion Due to Wave Uprush", *Proceedings of the 19th Coastal Engineering Conference*, ASCE, pp 1553-1558.

Fisher, J. S., Overton, M. F., and Chisholm, T. 1986. "Field Measurements of Dune Erosion", *Proceedings of the 20th Coastal Engineering Conference*, ASCE, pp 1107-1115.

Hwang, K. 1995. "Predictive Model for the Dune Erosion and Swash Hydrodynamics", *Ph.D. Dissertation* in preparation, North Carolina State University, Raleigh, NC.

Mase, H., and Iwagaki, Y. 1984. "Run-Up of Random Waves on Gentle Slopes", *Proceedings of the 19th Coastal Engineering Conference*, ASCE, pp 593-609.

Overton, M. F., Fisher, J. S., and Young, M. A. 1988. "Laboratory Investigation of Dune Erosion", *Journal of Waterway, Port, Coastal and Ocean Engineering*, ASCE, Vol. 114, No. 3, pp 367-373.

Stive, M. J. F. 1984. "Energy Dissipation in Waves Breaking on Gentle Slopes", *Coastal Engineering*, Vol. 8, pp 99-127.

Thieke, R. J., and Sobey, R. J. 1990. "Cross-shore Wave Transformation and Mean Flow Circulation", *Coastal Engineering*, Vol. 14, pp387-415.