CHAPTER 241

Comparisons of Erosion Models For Storms at Ocean City, MD

Jie Zheng[1] and Robert G. Dean[2]

Abstract

A new non-linear cross-shore sediment transport model called CROSS is developed based on equilibrium beach profile concepts and scaling relationships. CROSS and three other existing models, CCCL (Chiu and Dean 1984), EDUNE (Kriebel 1989) and two versions of SBEACH (version 2.0, Larson and Kraus 1989, and version 3.0, undocumented) are investigated by comparing erosion occurring from November 1991 to January 1992, at Ocean City, Maryland, the site of a major beach fill placed by the State of Maryland and Federal Government in 1988, 1990 and 1991. Among the four models, CCCL is the only one which overpredicts average dune erosion; the other three underpredict it. Overall CROSS and EDUNE yield better predictions than the other two models.

Introduction

Ocean City, Maryland, is located on Fenwick Island, a north-south oriented barrier island of the central Delaware-Maryland-Virginia coast. The Ocean City beach was nourished by the State of Maryland in 1988, and the Federal Government in 1990 and 1991 to protect the city against storm damage (Stauble et al. 1993). The project layout is shown in Figure 1. The entire project was finished in August 1991.

After the project, a series of storms occurred in late 1991 and early 1992. Among these 1991-1992 winter storms, the January 4, 1992 storm was very severe with a peak storm surge of 2 meters (Jensen and Garcia 1993). The initial pre-storm beach profiles were surveyed on November 2-4, 1991, and the post-storm profiles were surveyed on January 11, 1992. In this period, an additional storm occurred on November 11, 1991. For consistency with the measured pre-storm and post-storm profiles, both the November 1991 and January 1992 storms are included in the numerical simulations. A total of seven survey lines located from the southern (37th

[1] Coastal Engineer, Coastal Technology Corporation, 3625 20th St., Vero Beach, FL, 32960, USA.

[2] Professor, University of Florida, 336 Weil Hall, Gainesville, FL 32611, USA.

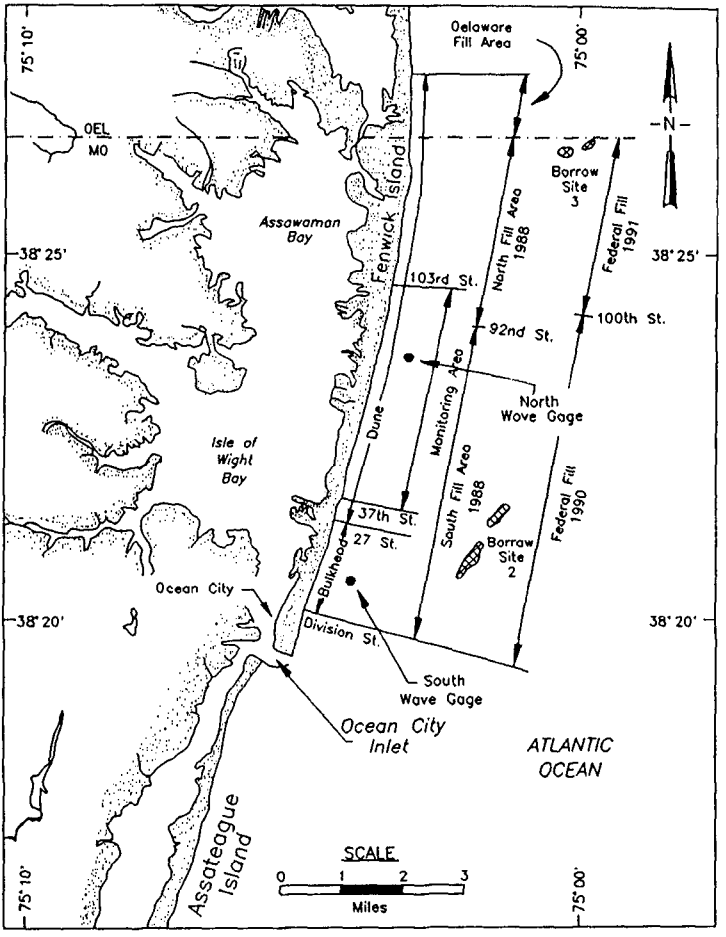

Figure 1. The Ocean City beach nourishment project layout.

Street) to northern (124th Street) portion of the project are available for both pre and post-storm surveys (Stauble et al. 1993, and Kraus and Wise 1993).

Four cross-shore sediment transport models are compared for the simulations of beach erosion at Ocean City during the November 1991 and January 1992 storms. These models are

- CCCL (Chiu and Dean 1984, 1986)
- EDUNE (Kriebel and Dean 1985, Kriebel 1986)
- SBEACH (Larson and Kraus 1989, Larson et al. 1989)
- CROSS (Zheng 1996, Zheng and Dean 1996)

Two versions (2.0 and 3.0) of SBEACH models will be included in the following comparisons. Version 3.0 was released in September 1994 by the U.S. Army Corps of Engineers after a study of storm erosion at Ocean City during the 1991-1992 winter storms. Three measures are presented for comparison of quantitative model performance.

Brief Description of Four Models

All four models discussed here are of the "closed loop" type and based on equilibrium beach profile concepts, which consider beach profile changes to be caused by deviations of a profile from its equilibrium. An equilibrium beach profile represents a dynamic balance of constructive and destructive forces acting on the beach. A change in the two competing types of forces will result in a disequilibrium. Considering wave energy dissipation per unit volume to represent the dominant destructive force, Dean (1977) proposed that a sediment of given size will be stable in the presence of a particular level of wave energy dissipation per unit volume, D_*, which is expressed as

$$D_* = \frac{1}{h}\frac{d(Ec_g)}{dy} \tag{1}$$

where h is the water depth, y is the shore-normal coordinate directed offshore, E is the wave energy density, and c_g is the wave group velocity. As a first approximation, D_* is assumed to dependent only on sediment size (Moore, 1982). With linear wave theory and shallow water assumptions, Eq (1) is integrated to

$$h = \left(\frac{24D_*}{5\rho g\sqrt{g}\,\kappa^2}\right)^{2/3} y^{2/3} = A\,y^{2/3} \tag{2}$$

where κ is the ratio of breaking wave height to water depth, and A is defined as a profile scale parameter.

CCCL Model

Under erosive water level and wave conditions, the time dependent beach recession, R(t) is given by

$$R(t) = R_\infty(1 - e^{K_R t}) \tag{3}$$

where R_∞ is equilibrium recession and K_R is a reciprocal time scale. At each time step, the equilibrium profile and recession are calculated by considering Eq. (3) and sand conservation. After the final computational time step, a factor of 2.5 is applied to the recession, in part to incorporate the alongshore variability of beach erosion.

EDUNE Model

The cross-shore sediment transport rate per unit beach width, Q, is considered as linearly proportional to the deviation of local wave energy dissipation per unit volume from the equilibrium,

$$Q = K_e(D - D_*) \tag{4}$$

where K_e is an empirical transport parameter and D is the local wave energy dissipation per unit volume. A beach steeper or milder than the equilibrium at a given depth will cause sediment transport offshore or onshore, respectively. Since the transport (Eq. (4)) has two variables, a continuity equation is used to close the system.

SBEACH Model

The cross-shore sediment transport rate is determined by

$$\begin{aligned} Q &= \pm K_s \left| D - D_* + \frac{\epsilon}{K_s}\frac{\partial h}{\partial x} \right|, \qquad D > D_* - \frac{\epsilon}{K_s}\frac{\partial h}{\partial x} \\ &= 0, \qquad\qquad\qquad\qquad D \le D_* - \frac{\epsilon}{K_s} \end{aligned} \tag{5}$$

where ϵ is an empirical constant and K_s is a transport coefficient. This relationship is similar to EDUNE except for the last term which incorporates the effect of local slope. The beach profile evolution is solved by combining the transport relationship with the continuity equation. The direction of transport (± in Eq. (5)) is determined according to

$$\begin{aligned} \frac{H_0}{L_0} - 0.00070\left(\frac{H_0}{w_f T}\right)^3 < 0, \quad + \\ \frac{H_0}{L_0} - 0.00070\left(\frac{H_0}{w_f T}\right)^3 > 0, \quad - \end{aligned} \tag{6}$$

CROSS Model

Based on scale analysis and the Froude relationship, the cross-shore sediment transport rate per unit beach width, Q, should scale as

$$Q_r = L_r^2 / T_r = L_r^{3/2} \tag{7}$$

where L_r and T_r are length and time scales, respectively. To satisfy this scale relationship (7) and ensure convergence to the equilibrium beach profile, the following sediment transport relationship is proposed

$$Q = K_c(D - D_*)^3 \tag{8}$$

where K_c is a dimensional constant. Time dependent profile response is determined by solving the transport equation (8) and sand conservation equation.

Storm and Beach Profile Characteristics

Water depth and profile elevations used here are referenced to NGVD (National Geodetic Vertical Datum), which lies 2 cm below mean water level for Ocean City. The wave height, wave period and storm surge time histories during the two storms were measured by two gages located directly offshore of Ocean City in a water depth of 10 meters. The measured significant wave height, peak spectral wave period and storm surge are shown in Figure 2 for the January 4, 1992 storm (Stauble et al. 1993).

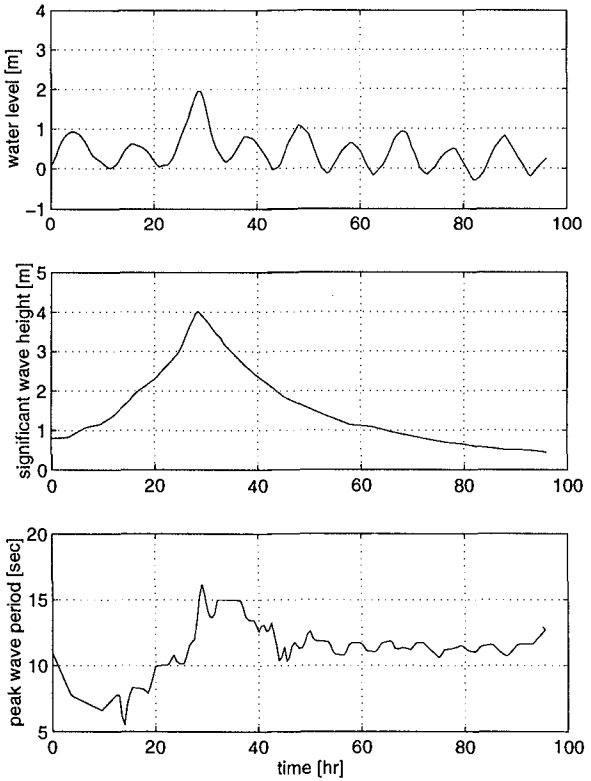

Figure 2. Water level, significant wave height and peak spectral wave period time history for the January 4, 1992 storm at Ocean City, MD (From Stauble et al. 1993).

Seven survey lines located at 37th, 45th, 56th, 74th, 103rd and 124th Streets (Stauble et al. 1993, Kraus and Wise, 1993) have both pre-storm and post-storm measured profiles available and are simulated. The mean grain sizes within each of 11 cross-shore morphologic zones are presented in Table 1. The seven measured pre- and post-storm profiles are shown in Figure 3 for the two surveys taken on November 2, 1991 and January 11, 1992, respectively. It appears that the storm-caused erosion is

Table 1 Average mean grain size in millimeters.

Sample Location	37th St.	45th St.	56th St.	63rd St.	74th St.	103rd St.	124th St.
Dune base	0.35	0.34	0.33	0.39	0.39	0.44	0.44
Berm crest	0.29	0.31	0.34	0.35	0.35	0.38	0.38
Mean-tide line	0.32	0.30	0.27	0.27	0.29	0.38	0.38
Swash zone	0.34	0.38	0.44	0.47	0.48	0.39	0.39
Nearshore trough	0.31	0.33	0.36	0.45	0.47	0.81	0.81
Nearshore bar	0.29	0.36	0.46	0.44	0.46	0.34	0.34
- 1.52 m contour	0.29	0.26	0.21	0.26	0.32	0.23	0.23
- 3.05 m contour	0.21	0.21	0.22	0.22	0.21	0.21	0.21
- 4.57 m contour	0.20	0.22	0.24	0.21	0.22	0.21	0.21
- 6.10 m contour	0.29	0.23	0.14	0.15	0.28	0.17	0.17
- 7.62 m contour	0.34	0.25	0.13	0.12	0.17	0.16	0.16

quite different for profiles at different locations. After two storms, the profiles at 37th and 56th Streets had almost no erosion, whereas the other profiles experienced quite severe losses in the dune area. Based on the measured profiles, the net volume changes are calculated for each profile and presented in Table 2. It appears that the net volume changes during the two storms are quite different from zero for most profiles due to the gradients in longshore sediment transport. To remove this effect, each post-storm profile is adjusted by shifting the profile horizontally a distance Δy to yield zero net volume change. The value of Δy is calculated by

$$\Delta y = \frac{1}{h_{total}} \int_{y_0}^{y_*} (h_{mb} - h_{ma})\, dy \tag{9}$$

where subscripts *mb* and *ma* denote profile elevation measured before and after storms, respectively, y_0 and y_* are offshore directed coordinates at the baseline and the limit of offshore profile change, respectively, and h_{total} represents the total elevation of the active storm profile. The sign of Δy is positive for a seaward translation. The profile retreat at the 3 meter contour and the eroded volume with and without the shifting adjustments are shown in Table 3. These parameters will be used as measures of the storm erosion and the performance of the numerical models.

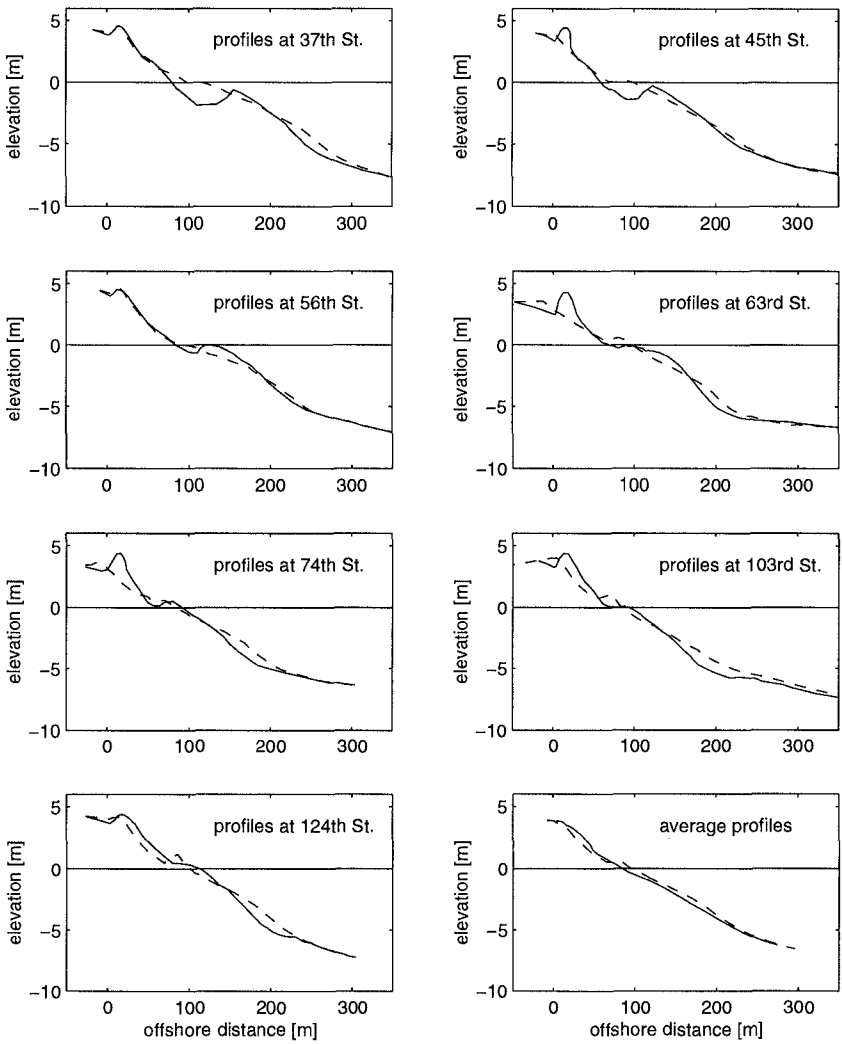

Figure 3 Measured pre-storm (solid line) and post-storm (dashed line) profiles.

Input Conditions for Each Model

The predictions of the four models are compared with the storm erosion measured at Ocean City, Maryland. The input parameters for each model in this study are selected to represent the conditions for which each model was calibrated. Among the four models, CROSS is the only one which can incorporate variable sediment size along a profile. The conditions run for each model are described briefly as follows.

Table 2 Measured volume change during the storm and adjustment Δy.

Street	Volume change (m^3 / m)			Adjustment Δy (m)	h_{total} (m)
	Gain	Loss	Net		
37th	158.77	20.78	137.99	-11.29	12.22
45th	81.01	49.42	31.59	-2.83	11.16
56th	27.71	47.96	-20.25	1.97	10.28
63rd	82.34	83.99	-1.65	0.16	10.31
74th	80.53	59.61	20.92	-2.19	9.55
103rd	136.06	56.33	79.73	-7.09	11.25
124th	75.74	56.10	19.64	-1.80	10.91
Average	55.71	24.97	30.74	-3.04	10.11

CCCL Model

This model has been used in establishment of the Coastal Construction Control Line (CCCL) in Florida. The CCCL is a line which depicts the landward limit of impact of a 100 year period storm event. The default dune slope is set to 1. Since this model cannot represent variable sediment size along a profile, a uniform grain size of 0.35 mm is applied. At each time, the significant wave height is used as the input wave height. The set-up at the shoreline is calculated based on linear wave theory as 0.23 times the incoming wave height. No wave run-up is included in the model. After running the storms, consistent with model calibration, a factor of 2.5 is applied to those contours which receded. This model does not incorporate a transport equation, but rather considers the profile to approach equilibrium with a folding time scale of 13 hours.

EDUNE Model

The default input dune slope is set to 1 and the input shoreline slope is taken as 0.05 which is the average shoreline slope of the measured pre-storm profiles. For the same reason as described for the CCCL model, a sediment size of 0.35 mm is used. The significant wave height is input at each time step. In EDUNE, the wave run-up is an input parameter held constant throughout the erosion simulation, and is used to control the location of the dune scarp above the peak water flood level. For the Ocean City storm erosion simulations, the run-up was fixed as 0.91 meters and 1.52 meters for the November 1991 and January 1992 storms, respectively, and was based on a combination of matching elevation of dune scarps and Hunt's equation (1958)

$$R = F_R H_b \frac{m}{\sqrt{H_b / L_0}} \tag{10}$$

where R is the run-up height measured vertically upward from the storm water level, F_R is a non-dimensional coefficient and is approximately 1, m is the average bed slope

from the run-up limit to the breaking point, and L_0 is the deep water wave length. In the application here, it was found that the best agreement was provided by using the maximum significant wave height of each storm in Eq. (10). The transport coefficient, K_e, for this application is the program default value of 8.73×10^{-6} m^4/N.

SBEACH Model

Both versions (2.0 and 3.0) of SBEACH model are believed to incorporate wave run-up and set-up. The maximum slope that a predicted profile is allowed to achieve is required and is set to 17.5^o as a default condition; this corresponds to a beach slope of 0.32. A constant sediment size of 0.35 mm is applied here, which was recommended by Kraus and Wise (1993) in their study. Both versions of the SBEACH model provide a choice of wave type (monochromatic or irregular). The option of irregular waves which requires an input of time history of significant wave height was chosen for this study. The default value for the transport coefficient, K_s, in both version is 1.50×10^{-6} m^4/N.

CROSS Model

The dune slope and the offshore slope are set equal to 1 and 0.5, respectively, as default conditions, and the shoreline slope is set to the average shoreline slope of the measured pre-storm profiles (0.05). Two different sediment size distributions are compared in this model. First, along each measured profile, the variable sand size listed in Table 1 is applied. Second, as a basis for comparison with the other three models, a uniform grain size of 0.35 mm is used. During each storm, a random wave series is generated according to the time history of the measured significant wave height and spectral peak wave period. The wave-by-wave set-up is calculated based on linear wave theory, and the wave run-up limit is established from Hunt's Equation (10). A transport coefficient value, K_c, of 7.14×10^{-10} m^8s^2/N^3 is used for this field application.

Numerical Results and Comparisons

The numerical results from the four models are quantified in terms of several parameters. A comparison of measured and predicted entire active profile changes is provided by the residual parameter, Res, defined in non-dimensional form as:

$$Res = \frac{\sum_{i=1}^{n} (h_{pi} - h_{mai})^2}{\sum_{i=1}^{n} (h_{mbi} - h_{mai})^2} \tag{11}$$

where h is the profile elevation, the subscripts "p" and "m" denote predicted and measured, respectively, "b" and "a" indicate before and after storm conditions, respectively, "i" represents the i^{th} location on the profile, and the sums extend across the entire active profile. The minimum possible value of Res is zero, which would correspond to a perfect simulation. If the numerical simulation predicts no changes, the value of Res is 1, which therefore should represent an upper limit of Res.

The dune erosion agreement between calculated and measured values is quantified by the eroded volume and the beach retreat at the 3 meter contour. To provided a measure of erosion and retreat, two different errors are presented: the mean square error, ERR_{ms}, and the algebraic average error, ERR_{ave}. These are expressed as

$$ERR_{ms} = \frac{\sum_{j=1}^{n} (S_{pj} - S_{mj})^2}{\sum_{j=1}^{n} S_{mj}^2}$$

$$ERR_{ave} = \frac{\sum_{j=1}^{n} S_{pj} - S_{mj}}{\sum_{j=1}^{n} S_{mj}} \qquad (12)$$

where S is an eroded volume or beach retreat, the subscripts "p" and "m" again represent the predicted and measured values, respectively, and "j" means the j^{th} beach profile. ERR_{ms} represents a factor of simulation accuracy and ERR_{ave} provides a measure of over or under-prediction of erosion. Compared with the measure, Res, which is based on local differences across the entire active profile, ERR_{ms} and ERR_{ave} are based on average differences of eroded volume or beach retreat at a particular elevation.

Comparisons between predictions and measurements for the profiles at 45^{th} Street are presented in Figure 4. The ridge features presented on the measured post-storm profiles suggest that there was some beach recovery even though the post-storm profiles were measured only a week after the second storm. The predictions of CROSS with both variable and uniform sand size are presented. It appears that the results predicted with variable sand size provide more reasonable simulations for dune erosion while the predictions with the uniform sand size fit the entire profile better. After applying the factor of 2.5 to those contours which receded, the CCCL model tends to overpredict erosion for most profiles. Since the application purpose of CCCL is to establish the Coastal Construction Control Line, the 2.5 factor is included to incorporate the variability of beach erosion at different locations. As mentioned above for EDUNE, the wave run-up is determined, in part, according to measured post-storm profiles used throughout the entire time of numerical simulation. Since beach erosion is quite sensitive to water level, the numerical results of EDUNE will depend greatly on the storm duration time and the input of wave run-up. Among all four models, SBEACH version 2.0 is the only model which represents the offshore bar feature. The newly modified version 3.0 of SBEACH presents substantially better agreement than version 2.0.

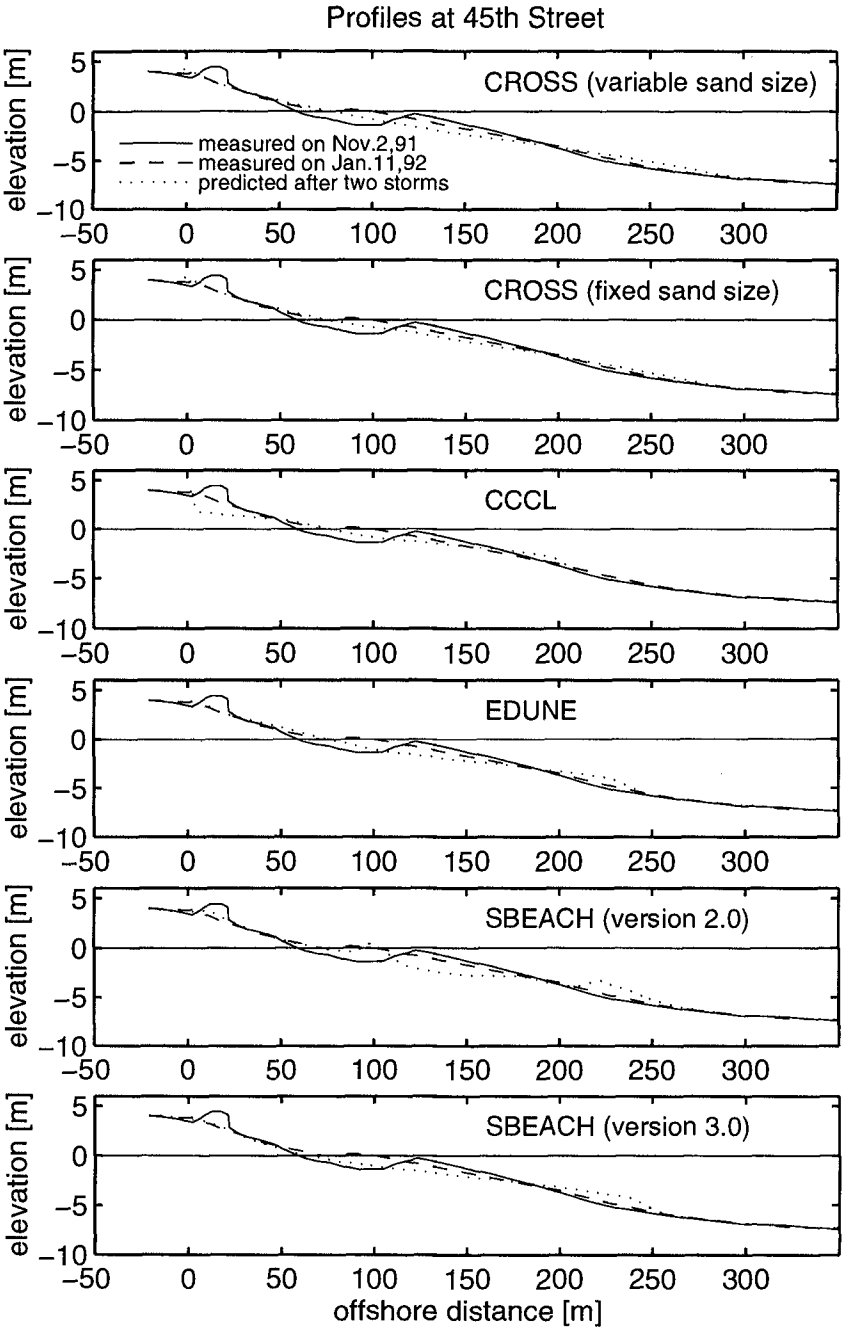

Figure 4. Comparisons of predicted and measured profiles at 45th Street.

The corresponding residuals, eroded volumes and beach retreat at the 3 meter contour for each individual profile were calculated. Two examples of profiles at 45th and 103rd Streets are shown in Table 4. Because the net volume changes between measured pre-storm and post-storm profiles are quite different from zero due to gradients of longshore sediment transport, in addition to the measured profiles, results are included based on shifting each post-storm profile the horizontal distance, Δy, to yield zero net volume change. In the table, "without adjustment" means data given by the original measured post-storm profiles, while "with adjustment" means data resulting from horizontally shifted post-storm profiles. Since all four models discussed here included only cross-shore sediment transport, the data presented "with adjustment" are considered to be more appropriate.

Table 4 The residuals, eroded volumes and beach retreat at the 3-meter contour.

Profile	Model	Residual		Eroded vol. (m^2)	Retreat at 3-m contour (m)
		w/o adjust.	With adjust.		
45th St.	CROSS(var. sand size)	0.525	0.496	20.13	8.71
	CROSS(fixed sand size)	0.287	0.280	19.39	8.36
	CCCL	1.067	0.851	60.56	18.34
	EDUNE	0.624	0.604	18.30	6.51
	SBEACH (ver. 2.0)	1.018	0.971	15.21	2.96
	SBEACH (ver. 3.0)	0.736	0.713	23.34	6.79
103rd St.	CROSS(var. sand size)	0.329	0.274	35.18	15.23
	CROSS(fixed sand size)	0.261	0.251	28.88	13.41
	CCCL	2.233	1.499	123.05	28.92
	EDUNE	0.548	0.413	54.66	20.04
	SBEACH (ver. 2.0)	0.596	0.590	19.54	7.03
	SBEACH (ver. 3.0)	0.510	0.433	35.20	10.61

The residuals averaged over the seven measured profiles and the two errors defined in Eq. (11) for eroded volume and beach retreat at the 3-m contour with respect to the horizontal shifted profiles are presented in Table 5. Overall, CCCL overpredicts the dune erosion during the two storms, whereas the other three models underpredict it. It appears that CROSS with fixed sand size results in significantly less average residual than the others. The dune erosion errors of CROSS with variable sand size, EDUNE and SBEACH version 3.0 are comparable. It is noticed that dune overwash occurred during the January 1992 storm. Among the four models, only EDUNE and SBEACH incorporate dune overwash processes. In the CROSS model, the profile shoreward of the dune crest is treated as a horizontal beach with the same elevation as

the dune crest. Therefore, the numerical simulations of CROSS do not include the dune erosion part caused by overwash. It is expected that the underpredictions of CROSS could be improved by incorporating dune overwash processes in the model.

Table 5 The average residuals and errors of eroded volume and beach retreat at the 3-meter contour with respect to the horizontally shifted measured profiles.

Model	Averaged residual	Error of eroded volume		Error of retreat	
		ERR_{ms}	ERR_{ave}	ERR_{ms}	ERR_{ave}
CROSS (variable sand size)	0.725	0.227	-0.401	0.283	-0.359
CROSS (fixed sand size)	0.458	0.319	-0.511	0.327	-0.444
CCCL	1.331	0.707	0.847	0.480	0.561
EDUNE	0.792	0.182	-0.328	0.260	-0.324
SBEACH (ver. 2.0)	1.211	0.470	-0.663	0.623	-0.749
SBEACH (ver. 3.0)	0.752	0.183	-0.399	0.259	-0.479

Summary

This paper has presented comparisons of the predictions of the CROSS model and three other commonly used closed loop models (CCCL, EDUNE and SBEACH) for storm erosion at Ocean City, Maryland during the November 1991 and January 1992 storms. The "2.5" factor was applied in the CCCL model in this comparison. The wave run-up parameters used in the EDUNE model are determined according to the measured post-storm profiles and the maximum significant wave heights during two storms. Seven survey lines located from the southern (37^{th} Street) to northern (124^{th} Street) portions of the project are selected for evaluation of the four models. In most locations, the net volume changes in profiles are quite different from zero due to gradients in longshore transport. An adjustment is made by shifting the whole profile horizontally a distance Δy to yield a zero net volume change for each profile.

A non-dimensional mean square residual parameter is provided to evaluate the agreement between the entire measured and predicted profiles (including subaerial and subaqueous parts). Two kinds of error averaged with different methods (mean square and algebraic average) are provided to evaluate the prediction of dune erosion. It appears that the residuals are less affected by the shifting adjustment, while eroded volumes and beach retreat are affected more significantly by the shift. Among the four models, the CCCL model is the only one which overpredicts average dune erosion. CROSS yields the least average residual and presents the best prediction for an entire profile (including both subaerial and subaqueous parts). For errors of eroded volume and beach retreat, CROSS with variable sand size, EDUNE and SBEACH (version 3.0) provide reasonably comparable predictions. It is anticipated that by incorporating dune overwash, the under prediction of dune erosion by CROSS can be reduced.

References

Chiu, T.Y. and Dean, R. G. 1984. "Methodology on coastal construction control line establishment," *Tech. and Design Memorandum 84-6,* Beaches and Shores Resource Center, Florida State University, Tallahassee, FL.

Chiu, T.Y. and Dean, R. G. 1986. "Additional comparisons between computed and measured erosion by hurricanes," *Technical Report,* Beaches and Shores Resource Center, Florida State University, Tallahassee, FL.

Dean, R.G. 1977. "Equilibrium beach profiles: U.S. Atlantic and Gulf Coasts," *Ocean Engineering Report No. 12,* Department of Civil Engineering, University of Delaware.

Hunt, I.A. Jr. 1958. "Design of seawalls and breakwaters," *U.S. Lake Survey,* Corps of Engineers, U.S. Army, January 1958.

Kraus, N.C. and Wise R.A. 1993. "Simulation of January 4, 1992 storm erosion at Ocean City, Maryland," *Shore and Beach,* Vol. 61 No. 1, pp. 13-22.

Kriebel, D.L. 1989. "Users manual for dune erosion model EDUNE."

Kriebel, D.L. 1986. "Verification study of dune erosion model," *Shore and Beach,* Vol. 54, No. 3, pp13-21.

Kriebel, D.L. and Dean, R.G. 1985. "Numerical simulation of time-dependent beach and dune erosion," *Coastal Engineering,* Vol. 9, pp. 221-245.

Larson, M. and Kraus, N.C. 1989. "SBEACH: Numerical model for simulating storm-induced beach change, Report 1: Theory and model foundation," *Tech. Report CERC 89-9,* CERC, US Army WES, Vicksburg, MS.

Larson, M., Kraus, N.C. and Byrnes M.R. 1989. "SBEACH: Numerical model for simulating storm-induced beach change, Report 2: Numerical formulation and model tests," *Tech. Report CERC 89-9,* CERC, US Army WES, Vicksburg, MS.

Stauble, D.K., Garcia A.W. and Kraus N.C. 1993. "Beach nourishment project response and design evaluation: Ocean City, Maryland. Report 1, 1988– 1992," *Tech. Report CERC 93-13,* CERC, US Army WES, Vicksburg, MS.

Zheng, J. 1996. "Improved cross-shore sediment transport relationship and model," *Ph.D. Dissertation,* University of Florida, Gainesville, Florida, U.S.A.

Zheng, J. and Dean, R.G. "Numerical modeling and intercomparisons of beach profile evolution," to appear in *Coastal Engineering.*