Improving Input Wave Data for Use with Shoreline Change Models

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Abstract: Shoreline change models such as GENESIS use refracted wave data identified at nearshore water depths that are seaward of the breaking limit for the largest waves in the model's ensemble. Adjustment of the manner in which wave data are input to the model can potentially improve the physical reality of the model's predictions. This paper presents a method whereby incipient breaking wave conditions are computed for each refracted wave case and then transformed offshore to a given reference water depth for subsequent input to the shoreline change model. This allows for consideration of wave transformations that occur between the reference water depth and the point of incipient breaking. This adjustment is shown to be of particular importance in those cases where the nearshore bathymetry is irregular.

INTRODUCTION

Numerical models such as GENESIS (Hanson 1987; Hanson and Kraus 1989) predict shoreline change as a result of a time series of incident wave events. To emulate the nearshore transformation of these events, the wave time series is first bin-sorted into groups, or "wave cases," of self-similar wave period and incident angle. For an assumed input wave height of unity, the average wave period and angle for each case is then refracted across a numerical grid that represents the nearshore bathymetry to be modeled. The combined refraction/shoaling coefficient $K_R K_S$ and the refracted wave angle at each alongshore column of the grid are then stripped from the results along a preestablished reference depth and subsequently used as input to the shoreline change model.

The preestablished reference depth d_R is located *seaward* of the breaking depth of the largest wave in the time series, and, for reasons of computational efficiency, is held constant for all wave cases. If the reference depth were shallower, the larger waves in the time series would be truncated in height to correspond to the maximum breaking wave height allowed by the selected reference depth. As a result, energy would be clipped from the wave's time series. For typical applications, this reference depth is therefore considerably deeper than the breaking depth for the majority of waves in the time series. For example, along southeast Florida, the appropriate reference depth may be about 5 m (to accommodate a maximum wave height of about 4 m), however, the majority of breaking wave heights are on the order of only 1 m.

The shoreline change model computes incipient breaking conditions along the shoreline by transforming the wave data from the reference water depth to the shoreline under the assumption of straight and parallel contours. This means that wave transformations due to irregular bathymetry between the reference depth and the point of incipient breaking are not considered by the shoreline change model—even though they were computed in the original wave refraction analysis from which the reference wave data were stripped. In instances where the nearshore bathymetry is irregular, such as adjacent to an inlet or other shoreline perturbation, this procedure can result in oversight of nearshore wave transformations important to predictions of sediment transport. A method to address this problem, which does not require alteration of the shoreline change model, is presented in the following.

METHOD

In this method, the wave time series is bin-sorted into cases of self-similar period and angle, and the average period and angle for each case is computed per standard GENESIS procedures. The average wave height is likewise computed for each case, and is transformed across the bathymetric grid for each wave case (instead of transforming a unit wave height). A single reference water depth d_R, is selected that is deeper than the breaking depth anticipated for the largest wave in the time series. Then, the incipient breaking wave height and angle are computed at each alongshore column of the refraction grid for each wave case. These incipient breaking wave conditions are then transformed back offshore to the reference depth d_R, under the assumption of straight and parallel contours. The resulting "backward-refracted" wave height is normalized by the value of the input wave height in order to yield the refraction/shoaling coefficient at the reference depth for each column of the grid and for each wave case. This value and the backward-refracted wave angle are input to the shoreline change model.

In practice, the incipient breaking wave conditions are computed by scanning the refracted wave data in a landward to seaward direction along each column of the grid. The purpose of the scan is to identify the first (landwardmost) occurrence of a nonbroken wave condition, that is, where the wave height H is less than κ times d, where κ is the breaking index (usually about 0.8). From the values of the refracted wave height and angle at this point, the incipient breaking wave height H_b and wave angle α_b can be computed. Specifically, from Green's Law and Snell's Law

$$H_b^2 C_{gb} \cos \alpha_b = H_1^2 C_{g1} \cos \alpha_1 \quad (1)$$

$$\frac{\sin \alpha_b}{C_b} = \frac{\sin \alpha_1}{C_1} \quad (2)$$

where H, α, C, and C_g = wave height, angle, celerity, and group celerity, respectively. The subscripts b and 1 refer to incipient breaking conditions and the landwardmost occurrence of the nonbroken wave, respectively. Eqs. (1) and (2) can be solved directly for incipient breaking conditions through the assumption that wave breaking occurs for shallow-water wave conditions; that is

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$$C_b = C_{gb} = \sqrt{gd_b} = \sqrt{g\frac{H_b}{\kappa}} \quad (3)$$

where g = acceleration due to gravity; and d = water depth. Using the identity $\sin^2 \alpha_b = 1 - \cos^2 \alpha_b$, Eqs. (1) and (2) can be combined as

$$H_b = H_1^{4/5}(C_{g1} \cos \alpha_1)^{2/5} \frac{g}{\kappa} \left[1 - \frac{H_b g \sin^2(\alpha_1)}{C_1^2}\right]^{-1/5} \quad (4)$$

and solved iteratively for H_b. Alternately, noting that $(H_b g \sin^2 \alpha_1/C_1^2)^2 < 1$, (4) can be solved directly for H_b through the approximation

$$H_b \simeq H_1^{4/5}(C_{g1} \cos \alpha_1)^{2/5} \left(\frac{\kappa}{g}\right)^{1/5} \left[1 + \frac{1}{5}\frac{H_b g \sin^2(\alpha_1)}{C_1^2}\right] \quad (5)$$

such that

$$H_b \simeq A_1 \left[1 - \frac{1}{5}A_1 A_2\right]^{-1} \quad (6)$$

where

$$A_1 = \left(\frac{\kappa}{g}\right)^{1/5} H_1^{4/5}(C_{g1} \cos \alpha_1)^{2/5} \quad (7a)$$

$$A_2 = (g \sin^2 \alpha_1)/C_1^2 \quad (7b)$$

The incipient wave breaking angle α_b is then found using (2) and (3).

The wave height H_R and angle α_R at the nearshore reference depth d_R are then computed from the breaking height H_b and angle α_b through (1) and (2); where, in this instance, the subscript 1 is replaced by the subscript R (i.e., the "reference" water depth condition). The latter values represent the so-called backward-refracted wave height and angle. To facilitate use with GENESIS (which assumes that the wave height data are input as the combined refraction/shoaling coefficient $K_R K_S$, not as a dimensional wave height), the value H_R must be divided by the value of the wave height that was input to the wave transformation model. The resultant normalized wave height and the computed angle serve as the input wave data to the shoreline change model; that is, in the case of GENESIS, the file named NSWAV*.

In applications where the nearshore profile features a narrow trough between the shoreline and the breaking bar, it is useful to use a test to eliminate translatory waves during the scan for incipient breaking conditions. Specifically, if the landwardmost occurrence of the nonbroken wave occurs for only one or two rows and is followed by the seaward occurrence of breaking across the bar, the scan continues in order to identify the first occurrence of the nonbroken wave conditions seaward of the bar feature. In the absence of this check, the incipient *shore* break may be identified instead of the active *bar* break.

It is noted that incipient wave breaking is a height-dependent process. In the present method, only one refracted wave height is used to identify incipient breaking conditions for each wave case. For wave heights that are larger than the selected height, the incipient breaking angle will be overpredicted, and vice versa. It is for this reason that the average wave height for each case is used as input to the wave transformation model—instead of an input wave height of unity. The number of waves for which the angle is overpredicted should be more-or-less offset by those for which the angle is underpredicted. Ultimately, this error is accommodated by the model's calibration. The error could be reduced by bin-sorting wave events by wave height as well as period and angle; however, this increases complexity.

EXAMPLE CALCULATION

Table 1 presents example wave height and angle data from a refraction analysis. The results are presented for a given "column" of the refraction grid where row numbers increase from land (row 1) to offshore (row 12), and where water depths have been specified for each row. The wave period is 9.0 s. The wave breaking index has been specified as $\kappa = H/d = 0.8$. Assume that the reference water depth for the shoreline change model has been selected as $d_R = 6.0$ m.

The shorewardmost occurrence of a nonbroken wave is found by scanning the column, beginning at row 1, for the case of $\kappa < 0.8$. This occurs at row 4. The incipient breaking wave height is estimated from (5) or (6), where H_1 and α_1 correspond to row 4; and C_1 and C_{g1} are computed from linear wave theory for the wave period (9 s) and the depth at row 4 (1.7 m). Specifically, for $\kappa = 0.8$, $g = 9.81$ m/s², $H_1 = 0.57$ m, $\alpha_1 = 3.6°$, $C_1 = 4.03$ m/s and $C_{g1} = 3.91$ m/s, (5) yields $H_b = 0.67$ m. The incipient breaking wave angle is computed from (2) and (3); viz., $\alpha_b = 2.56°$. Note that it is not proper to take the seawardmost occurrence of a broken wave (row 3) as the incipient breaking condition because the wave condition at this point is depth limited. The degree to which the wave has broken at this row may be much different than for the corresponding row in the adjacent column.

Using (1) and (2), the incipient breaking conditions, $H_b = 0.67$ m and $\alpha_b = 2.56°$, are now backward-refracted to the reference depth, $d_R = 6.0$ m. The values of $C_R = 7.29$ m/s and $C_{gR} = 6.60$ m/s are computed for 6.0 m depth, and one finds $H_R = 0.44$ m and $\alpha_R = 6.57°$. The reference wave height value $H_R = 0.44$ m is then normalized by the average wave height that was input to the wave transformation model to yield the combined refraction/shoaling coefficient, $K_R K_S$.

In the absence of this backward-refraction technique, the input wave conditions for this grid column would be taken from the row that corresponds to the reference water depth $d_R = 6.0$ m (row 11). From Table 1, these values are $H_R = 0.35$ m and $\alpha_R = -8.2°$. The shoreline change model, which assumes straight and parallel contours landward of the reference depth, would compute an incipient breaking condition of $H_b = 0.55$ m, and $\alpha_b = -2.9°$. This wave height is 18% lower—and the wave angle is 5.5° different (and in the opposite direction)—than that determined by the complete refraction analysis conducted landward of the reference depth. The resulting estimate of the longshore sediment transport will be 30% less and in the opposite direction than that that would be computed from the complete refraction analysis. This particular example is from a shoreline change investigation undertaken for a quasi-irregular, sandy coastline in Puerto Rico. It illustrates the error that can be introduced when refraction sea-

TABLE 1. Example Results from Refraction Analysis (Wave Period of 9.0 s)

Grid column (1)	Grid row (2)	Depth d (m) (3)	Wave height H (m) (4)	$\kappa = H/d$ (5)	Wave angle (deg.) (6)
7	1	0	0	—	0
7	2	0.3	0.24	0.80	1.5
7	3	0.7	0.56	0.80	3.4
7	4	1.7	0.57	0.34	3.6
7	5	2.9	0.52	0.18	3.8
7	6	3.7	0.50	0.14	4.2
7	7	3.4	0.45	0.13	4.2
7	8	2.9	0.43	0.15	2.8
7	9	3.8	0.39	0.10	−3.1
7	10	5.0	0.37	0.07	−6.8
7	11	6.0	0.35	0.06	−8.2
7	12	7.4	0.34	0.05	−9.0

ward of the models' reference depth is neglected along non-regular coastlines encountered in the prototype.

EXAMPLE APPLICATION

The requirement for this technique was identified while applying the GENESIS model to the shoreline downdrift of South Lake Worth Inlet ("Palm" 1995), located along the southeast, Atlantic coastline of Florida. The nearshore bathymetry features a wide bypassing bar that connects to the coastline about 900 m south of the inlet [Fig. 1(a)]. The nearshore reference depth d_R, which allows for inclusion of the largest waves in the hindcast time series is about 5.5 m.

Inspection of the transformed wave data indicated that some larger waves break on the seaward face of the bypassing bar; however, these breaking conditions likely govern sediment transport along the bar; whereas the shoreline changes appropriately predicted by GENESIS are governed by breaking of the reformed wave closer to shore. The technique prescribed herein allows for a judicial selection of breaking conditions to account for this phenomenon, whereas the standard GENESIS methodology does not.

Figs. 1(b and c) illustrates the breaking wave height and angle for one typical wave case. The breaking conditions traditionally computed by GENESIS (dashed line) are based on transformation of wave conditions from the nearshore reference depth to incipient breaking under the assumption of straight and parallel contours. The breaking conditions computed by this paper's method (solid line) are based on computation of incipient breaking near the shoreline directly from the wave refraction analysis. Considerable wave transformation is noted between the nearshore reference depth and the point of actual incipient wave breaking—particularly along

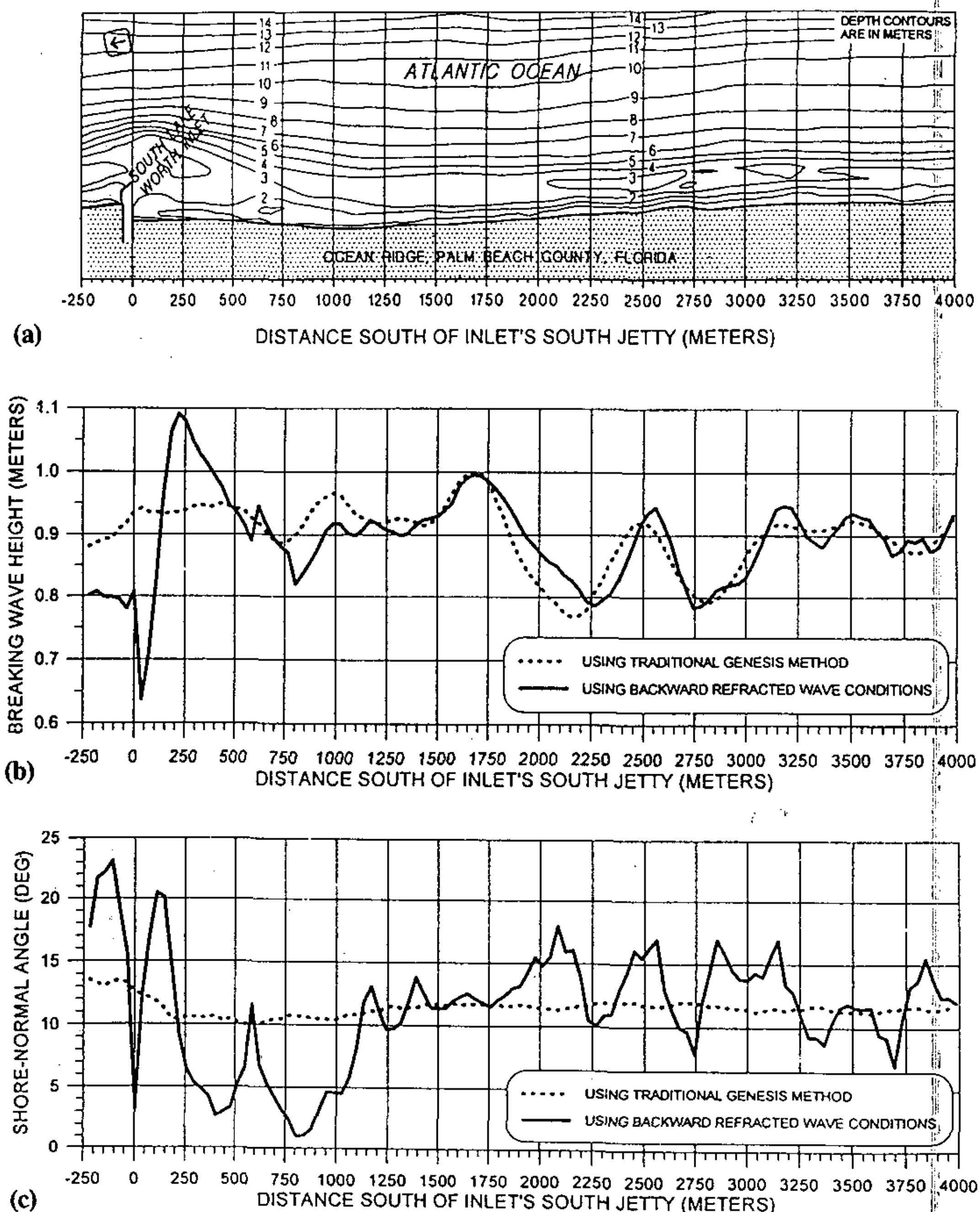

FIG. 1. Study Area Shoreline Illustrating (a) Nearshore Bathymetry (Depth Contours in Meters); (b) Breaking Wave Height and (c) Angle Computed by Traditional Application of GENESIS Methodology (Dashed Line) and by Identification of Incipient Breaking Conditions from Refraction Model (Solid Line) for Typical Input Wave Condition

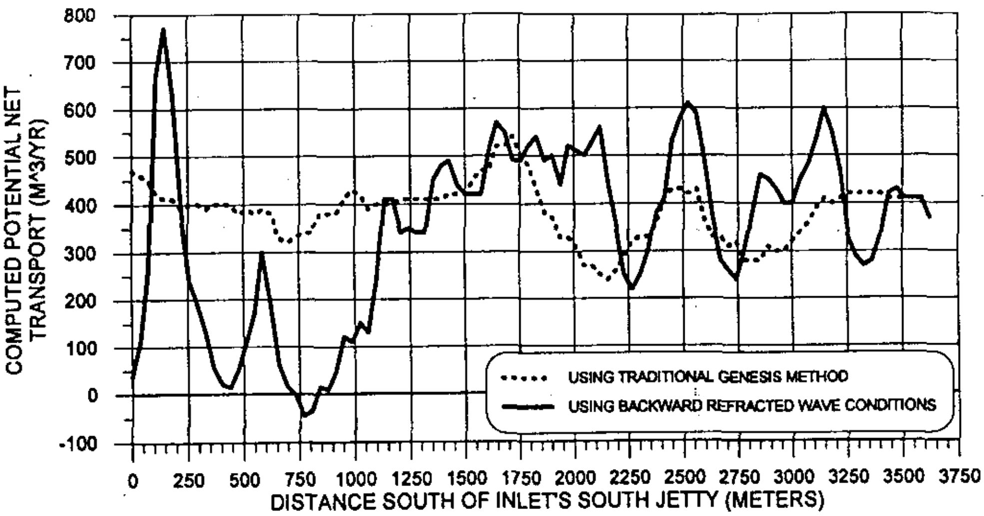

FIG. 2. Uncalibrated Net Longshore Sediment Transport Rate Computed along Study Area Shoreline Using Traditional GENESIS Application (Dashed Line) and Method Described in Present Paper (Solid Line)

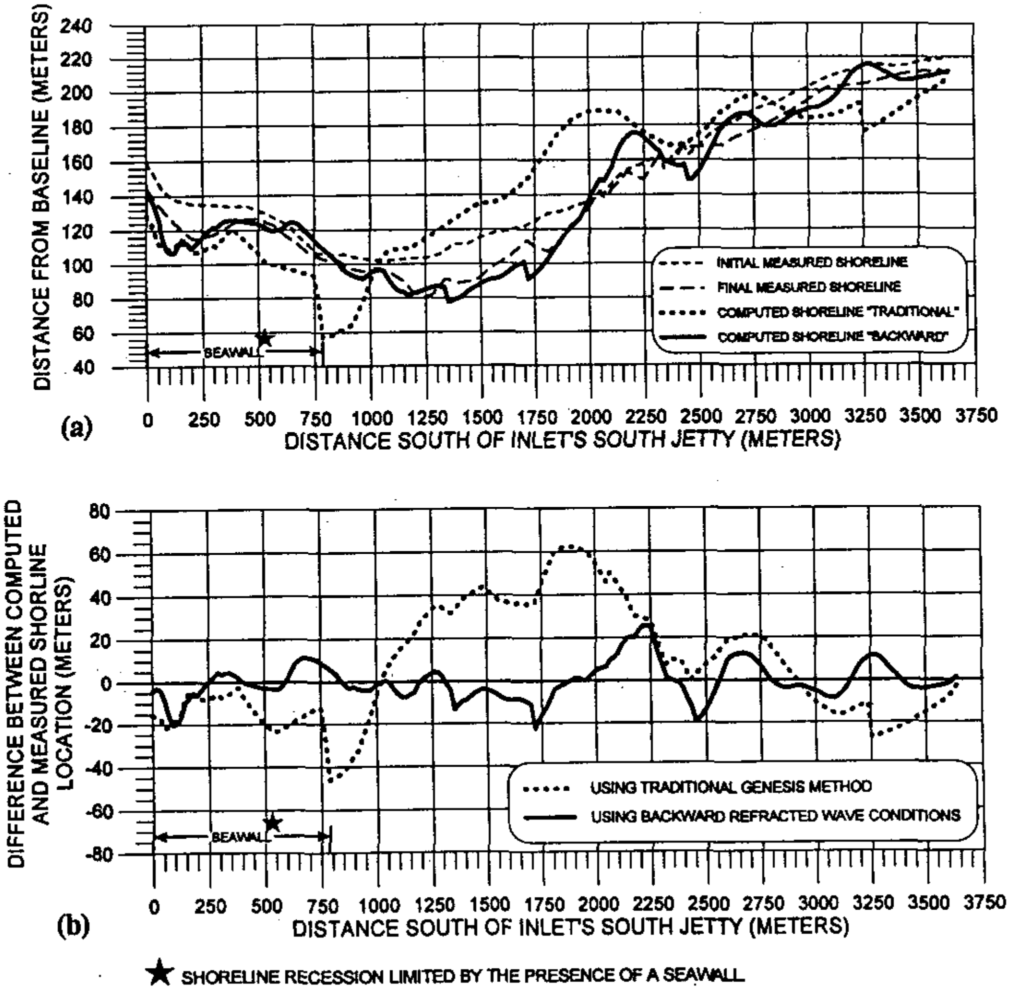

FIG. 3. Shoreline Locations Predicted by GENESIS Using Traditional Application (Heavy Dashed Line) and Method Described in Present Paper (*Heavy Solid Line*): *(a)* Measured Initial and Final (Target) Shorelines; (b) Agreement between Predicted and Measured (Target) Shorelines for Traditional Approach and Present Approach

that part of the coastline dominated by the inlet's bypassing bar.

Fig. 2 compares the net sediment transport rates computed by GENESIS from the wave time series for (1) wave data stripped directly from the nearshore reference depth (and transformed to breaking via straight and parallel contours); and (2) the incipient breaking conditions computed from the complete refraction analysis. The former fails to characterize the complex longshore sediment transport patterns that occur along the coastline leeward of the bypassing bar. That is, significant alongshore gradients in transport potential—associated with wave transformation across the bypassing bar—are not predicted when wave data stripped directly from the nearshore reference depth are used as input to GENESIS. In this case, the GENESIS cell spacing was 18.3 m and the inlet's south jetty was modeled as a nontransmissive structure. Fifteen active groins were included. Sand was "bypassed" into the model cells within 55 m of the inlet to emulate the inlet's fixed sand-bypass plant. Sand was likewise injected into the model cells between 930 and 1,190 m south of the inlet, in a normal-shaped distribution alongshore, to emulate sand moving onto the natural bypassing bar. The rate and magnitude at which sand was moved into or out of the cells was correlated to the wave time series and based, in part, on knowledge of the bypass plant's operations and the inlet's sediment budget and transport pathways.

Fig. 3(a) illustrates the GENESIS shoreline predictions for a 19-yr period using both the traditional and backward-refraction approaches. The initial and measured (target) shorelines are also depicted. The results represent the best overall shoreline agreement obtained from independent calibrations of each approach. Fig. 3(b) summarizes the alongshore difference in the predicted and measured shorelines for the two approaches. From the figure, it is evident that the paper's backward-refraction approach yields significantly closer and more uniform agreement between predicted and measured shorelines than does the traditional approach. In fact, the predictive ability of the traditional approach within 750 m of the inlet's south jetty is artificially improved because shoreline recession along this reach is limited by the presence of a seawall. Relative to the backward-refraction approach, the traditional approach yields the poorest prediction within 2,250 m south of the inlet. Along that stretch, the traditional approach fails to characterize the transport modulations nearest the inlet as well as the steep acceleration in net southerly transport between 750 and 2,000 m south of the inlet. The latter phenomenon results in shoreline erosion that is both measured in the prototype and correctly predicted by the backward-refraction method. In the present case, reliance on the traditional approach would have resulted in a failure to recognize several erosional "hot spots" along the modeled shoreline and a diminished appreciation of the refractive effects of the inlet's ebb shoal platform.

The backward-refraction approach yields greater oscillations in the alongshore transport rate beyond 2,000 m south of the inlet. These are attributable to nearshore bathymetric variations (bar/trough features), which may be temporaneous. In practice, the modeler may elect to smooth these variations—or adopt the results of the traditional approach therealong. Nonetheless, it is noted that the method's oscillatory transport values yielded shoreline agreement that was as good or better than the traditional approach. Hence, at least in the present case, it is not evident that use of the backward-refraction approach introduced anomalous bias along sections of shoreline with quasi-regular or temporaneously irregular bathymetry.

CONCLUSIONS

The method described herein can be used to develop input wave data for shoreline change models along areas where the nearshore bathymetry is irregular. In this method, incipient breaking conditions are computed from the complete refracted wave data and are then transformed back to common reference water depth specified for the shoreline change model. Application of this method allows for consideration of wave transformation that occurs between the reference water depth and the break point that is otherwise not considered in classical application of the shoreline change models. Failure to account for such wave transformation may lead to incomplete appreciation of the shoreline's transport patterns and potential for erosional behavior. The method also provides the derivative benefit of enabling the modeler to judiciously select the breaking wave conditions or (at the least) to inspect them. This method affects the manner in which wave conditions are computed and reported in the shoreline change model, and does not require modification of the model itself.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C = celerity;
C_g = group celerity;
d = water depth;
g = acceleration due to gravity;
H = wave height;
α = wave angle; and
κ = breaking index.

Subscripts

b = breaking;
R = reference; and
1 = location of landwardmost occurrence of nonbroken wave.

Bodge, K.R., Creed C.G. and Raichle, A.W. (1996). "Improving input wave data for use with shoreline change models." *Journal of Waterway, Port, Coastal, and Ocean Engineering,* American Society of Civil Engineers, Vol. 122, No. 5, New York, NY.

ERRATA SHEET

The correct expressions for Equations 4, 5, and 7b are as follows:

$$H_b = H_1^{4/5}\left(C_{g_1}\cos\alpha_1\right)^{2/5}\left(\frac{\kappa}{g}\right)^{1/5}\left[1-\frac{H_b g \sin^2(\alpha_1)}{\kappa C_1^2}\right]^{-1/5} \quad (4)$$

$$H_b \approx H_1^{4/5}\left(C_{g_1}\cos\alpha_1\right)^{2/5}\left(\frac{\kappa}{g}\right)^{1/5}\left[1+\frac{1}{5}\frac{H_b g \sin^2(\alpha_1)}{\kappa C_1^2}\right] \quad (5)$$

$$A_2 = \left(g\sin^2\alpha_1\right)/\left(\kappa C_1^2\right) \quad (7b)$$

Also, description in text between Equations 4 and 5 should read:

"Alternately, noting that $\left(\left(H_b g \sin^2\alpha_1\right)/\left(\kappa C_1^2\right)\right)^2 < 1$, (4) can be solved....."

In practice, subsequent to about 1995, Equations 3 through 7b have not been applied in the application of the "back-refraction" method. With recent improvements in the computational efficiency of computers, Equations 1 and 2 are now solved directly for H_b and α_b with numerical techniques. This obviates the use of the shallow water wave assumption that is requisite to Equations 3 through 7b.