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A Criterion for Determining the Impact on Shorelines Caused by Altering Wave Transformation

Jerome P.-Y. Maa, Carl H. Hobbs, III, and C. Scott Hardaway Jr.

Virginia Institute of Marine Science
School of Marine Science
College of William & Mary
Gloucester Point, VA 23062, USA.

ABSTRACT

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An evaluation of the possible influence of man-made changes to wave transformation processes at a particular site requires an extensive modeling effort that yields quantitative results suitable for decision-making. Analysis of a proposed offshore sand mining project at Sandbridge Shoal, near Virginia Beach, Virginia, serves as an example of such an evaluation. Using the criterion established in this study, it is demonstrated that the originally proposed separation of the sand resource into two dredging sites will cause unfavorable results at the shore. A favorable alternative is proposed which will reduce breaking wave height modulation along the coast, and thus, the gradient of longshore sediment transport rate.

ADDITIONAL INDEX WORDS: *Breaking wave height modulation, Sandbridge Shoal, Virginia Beach, longshore sediment transport rate.*

INTRODUCTION

Evaluation of possible shoreline changes caused by any manmade alterations on wave transformation processes requires a comprehensive modeling effort that yields quantitative results quantifying the alteration effects. A criterion to demonstrate the significance and consequences of these possible alterations is also needed for management decision-making.

Although studying the possible alteration of the near-by shoreline is the final objective, it is understood that interpreting the relationship between wave forcing and associated shoreline change is still an art. Formulations of the possible longshore sediment transport rate still can be very different for the same breaking wave condition (KOMAR and INMAN, 1970; GOURLAY, 1982; CERC, 1984; WRIGHT *et al.,* 1987). Because it is commonly accepted that breaking wave is the dominant factor that affects the evolution of shorelines, it would be logical to first focus our attention on changes in breaking waves. Only after a comprehensive calibration of these available longshore sediment transport models at the study site is accomplished, would it be appropriate to assess the possible responses of the shoreline. For this reason, this paper is an interim study on the possible effects on shoreline changes.

Beach nourishment using beach-quality sand from Sandbridge Shoal, an offshore deposit located approximately 5 km offshore (Figure 1), was proposed in the mid 1990's and, subsequently carried out in 1996 and 1998. Dredging of the shoal, however, caused concern that there may be increased beach erosion along the already severely eroded shoreline of Sandbridge. In order to understand the possible changes to waves (and thus, changes in the quantity of energy impinging upon the shore) that might be caused by dredging at the shoal, we carried out a comprehensive study of the wave climate, the possible modification on selected dredging areas, and the effects on wave transformation due to dredging at those areas. The earlier study (MAA and HOBBS, 1998) indicated that if the quantity of sand taken from Sandbridge Shoal was limited to around 10^6 m^3, the change in bottom topography may cause a possible change about 8% in the worst scenario (20 s waves, coming from NE). Even for these extremely long period waves, the change is much small, around 2%, if coming from other directions. For these typical Northeaster waves with periods on the order of 12 to 14 seconds, the change in wave height is negligible. Because the dredge site is sufficiently deep, short period waves were not affected. The chance of this possible 2–8% change is extremely small because of the unusual long period wave, and thus, it can be concluded that the effect is negligible. Permission was granted for limited sand mining.

Because of the great demand for beach-quality sand along Virginia's southeastern shore and the lack of other suitable sand sources, it is necessary to consider mining up to 2×10^7 m^3 from Sandbridge Shoal over the next two to 20 years. In this study, we address this possibility by examining the wave transformation process and developing a method to determine if the consequence is acceptable. We also included a summary of (1) a review of the proposed dredging site, (2) selection of model waves based on wave climate studies, (3) use of a wave transformation model to simulate the possible changes in breaking wave heights, and (4) development of a

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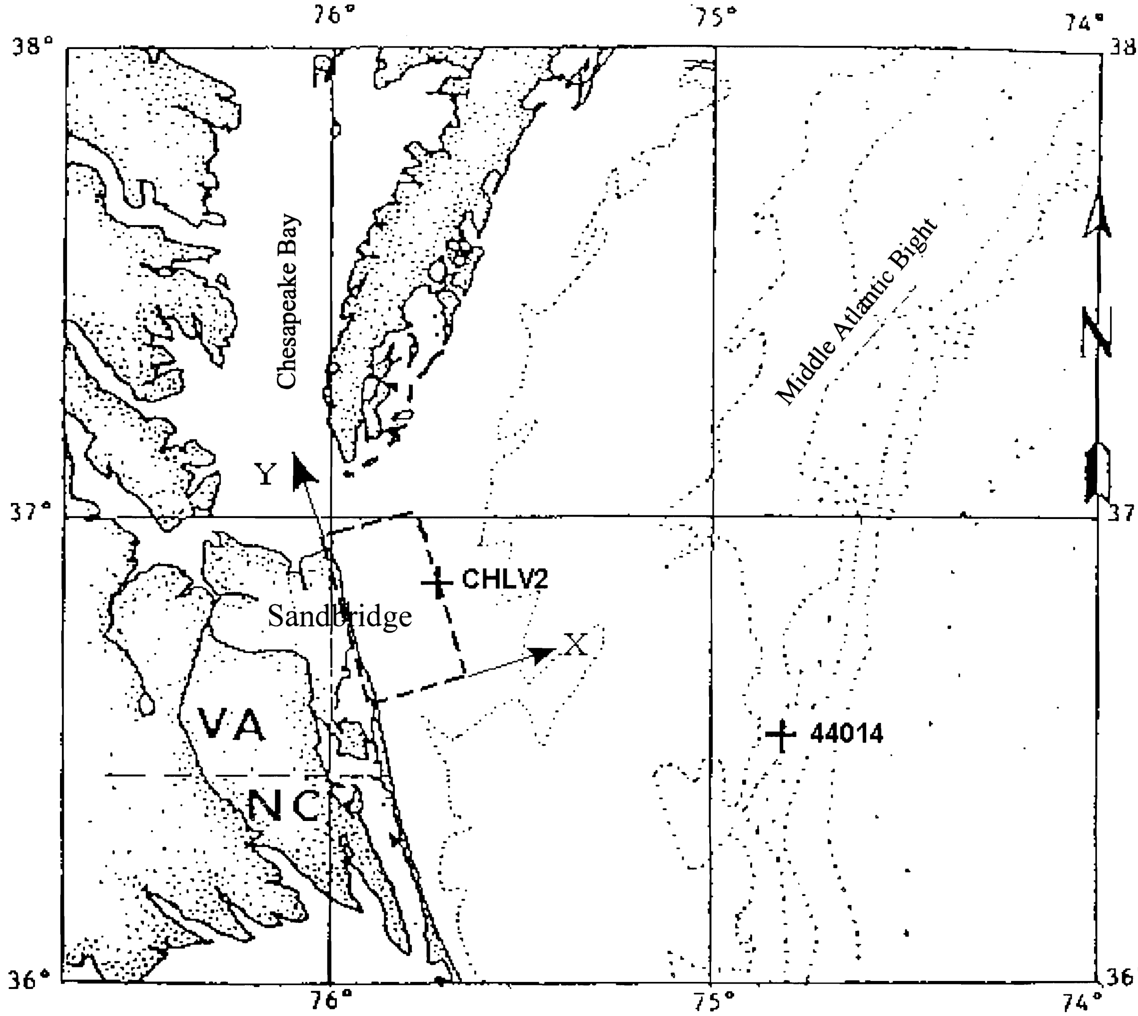

Figure 1. Location map indicating the study site and the offshore data buoys.

method to determine whether the possible changes would be positive or negative (*i.e.,* good or bad) in the view of shoreline managers. The focus is on the method of determining if the consequence would be beneficial or harmful to the nearby coast.

STUDY SITES

A computation domain of 24 × 45 km (dashed box in Figure 1) was established with a grid size of 30 × 60 m in the x and y directions, respectively. A small sub-domain is given in Figure 2 to show the detail of water-depth contours in the vicinity of Sandbridge Shoal. The originally proposed borrow area (Sites A and B in Figure 2) will yield about 2×10^7 m^3 of sand if dredged to 3 m below the present sea bottom.

Notice that after the completion of dredging at these two sites, a highly modified shoal will remain (Site C, the unmodified area between Sites A and B, Figure 2, because it would be necessary to relocate an existing cable) which may have an undesired influence on wave transformation. For this reason, we examined what would happen if dredging, though currently not planned, was performed at Site C.

Based on the above statements, we considered three scenarios: (1) Phase 1, dredging at Site A has been implemented, (2) Phase 2, dredging at borrow Site A and B have been implemented, and (3) Phase 3, dredging at the suggested extra borrow Site C has been also implemented. The likely total quantity of beach-quality sand at the three sites is about 3.1×10^7 m^3.

WAVE CONDITIONS

Based on the wave height and period measurements at NOAA wave station, CHLV2 (Figure 1), three categories of wave conditions were selected for modeling. These are (1) A northeaster with a wave height, H, of 1.9 m and a wave period, T, of 12 s; (2) a severe sea with $H = 3.0$ m and $T = 14$ s; and (3) the most severe sea with $H = 6.2$ m and $T = 20$ s (Maa and Hobbs, 1998). Because the minimum water depth at the shoal is about 10 m and the ambient water depth is

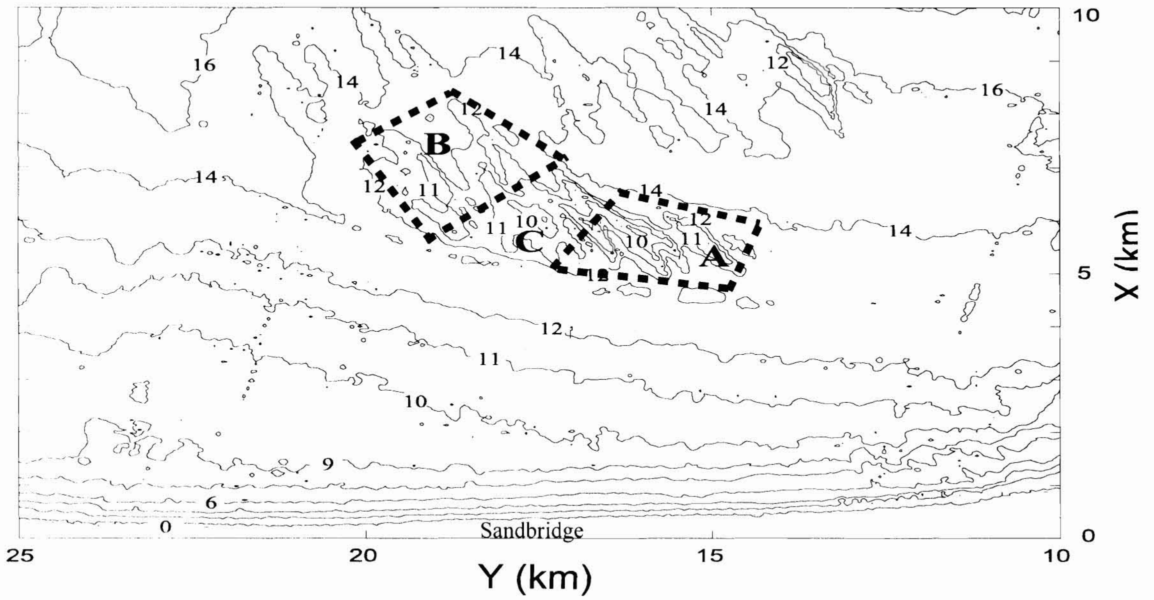

Figure 2. Bathymetric contours (in meter) in the vicinity of the proposed dredging sites, A and B. A suggested extra dredging site (Site C, the remaining shoal) is included for studying possible effects.

about 15 m, only long period waves would be affected by changes to the bottom.

We selected five possible wave directions for modeling based on the direction measurements from station 44014 (Figure 1). These five directions are evenly distributed between the NE and the E with the most frequent waves coming from the ENE. Other details of wave information and selection can be found in MAA and HOBBS (1998).

WAVE TRANSFORMATION MODEL

There are two kinds of wave transformation models: (1) Wave phase-averaged spectrum models and (2) wave phase-resolving models. The first group includes the WAN, STWAVE, and SWAN models. These models are capable of simulating wave growth, wave-wave interaction, wave refraction, and shoaling. They are not, however, capable of simulating wave diffraction, and their performance is not very good for shallow water areas, which is important for estimating breaking wave height required for computing longshore sediment transport. Also, their computation speed is low. For these reasons, we did not use them in this study.

The second group of models all solve the mild slope equation (BERKHOFF, 1972), or the extended mild slope equation (MASSEL, 1993; CHAMBERLAIN and PORTER, 1995; PORTER and STAZIKER, 1995; SUH *et al.*, 1997). The differences are in the ways they solve the equation. In other words, some models ignored some processes in order to achieve a better computing speed (EBERSOLE, 1985; KIRBY and DALRYMPLE, 1991). Some followed the exact way to solve the elliptic partial differential equation in order to accurately simulate more processes (MADSEN and LARSEN, 1987; LI and ANASTASIOU, 1992; ISOBE, 1994; LI, 1994; MAA and HWUNG, 1998). A comparison of these models and their limitations can be found elsewhere (MAA *et al.*, in press).

As pointed out by MCDOUGAL *et al.* (1996), a dredging pit may also cause wave diffraction and reflection. If the pit depth is much deeper than the ambient water depth and the pit size is comparable to the wave length, then wave reflection and diffraction can be strong. Fortunately, the planned dredging depth (3 m) is not large compared with the ambient water depth (~12 m) and the dredging pit size is also much larger than the possible wave length. For this reason, wave diffraction cannot be strong and wave reflection may be ignored.

Because of limits by the large spatial computing domain (24 km × 43.2 km) and available computer resources as well as by the understanding that only weak wave diffraction and negligible wave reflection are possible in the modeled area, only two models (REF/DIF-1 and RCPWAVE) are possible candidates. In this study, we arbitrarily selected the RCPWAVE model.

CRITERION TO DETERMINE THE INFLUENCE

When waves approach a coast, their trajectories may change because of wave refraction and diffraction. Finally waves break at a critical water depth, d_b, with a breaking wave height, H_b, and a breaking angle, α_b (the angle between wave crest line and the shore line). For a perfectly straight shoreline with parallel bathymetric contours, H_b and α_b will be the same at all places along the shoreline, *i.e.*, the wave breaking line will be parallel to the shoreline (see the ideal condition, the straight solid line, Figure 3). Under this condition, the longshore sediment transport rate is the same everywhere along the coast. If we only considered longshore

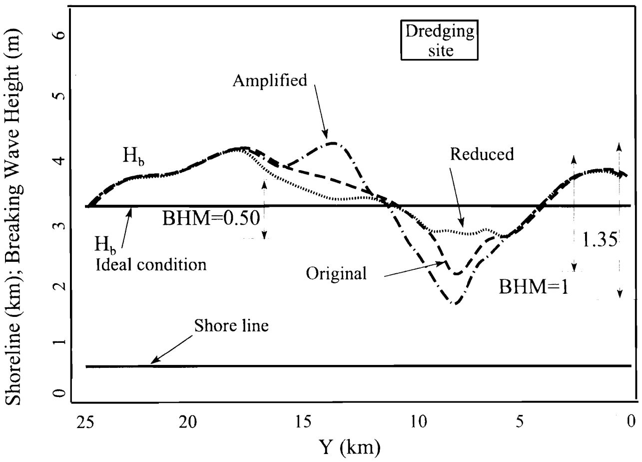

Figure 3. A concept diagram showing the longshore profile of breaking wave height for ideal conditions, an arbitrary selected real condition, and a favorable and unfavorable condition.

sediment transport, the shoreline would be the same throughout the area because sediment flux would be in an equilibrium state with identical quantities being imported and exported for any given wave condition. The advanced longshore sediment transport model presented by GOURLAY (1982) further demonstrates this point as follows.

Based on the pioneering work by KOMAR and INMAN (1970), GOURLAY (1982) proposed the following equation to calculate the immersed weight longshore sand transport rate, I(y) (in shore parallel direction):

$$I(y) = K^{*}(EC_g)_b \cos \alpha_b \left[\sin 2\alpha_b - \frac{K_{\Delta H}}{\tan \beta} \frac{\partial H_b}{\partial y} \right] \tag{1}$$

where $(EC_g)_b$ is the wave-energy flux at the breaking point, C_g is wave group velocity, $E_b = (1/8)\rho g H_b^2$ is wave energy, H_b is the breaking wave height caused by the significant wave height, $\rho = 1020$ kg/m^3 is water density, $g = 9.8$ m/s^2 is the gravitational acceleration, $\tan \beta$ is the average beach slope between the breaking point and the shoreline, $K_{\Delta H} = 23.7$, $K^{*} \approx 0.385 K_b$, and K_b depends on the Irribaren number, ξ, given as

$$\xi = \frac{2\pi \tan \beta}{H_b g T^2}. \tag{2}$$

When $\xi \geq 1.7$, $K_b = 1$, but when $\xi < 1.7$ then $K_b = 0.45\xi/K^{*}$.

Notice that the $\cos \alpha_b$ term on the right hand side of Eq. 1 was caused by the non-uniform alongshore current. In KOMAR and INMAN's (1970) analysis, this term was omitted because the alongshore current is uniform (GOURLAY, 1982).

The first term on the right hand side of Eq. 1 represents the longshore sediment flux caused by oblique breaking waves, with breaking angle α_b. The second term on the right hand side represents longshore flux induced by alongshore differences in wave set-up, which were caused by the alongshore gradient of one of the radiation stress components, $\partial S_{xx}/\partial y$ (LONGUET-HIGGINS and STEWART, 1962).

In Eq. 1, the breaking wave height, H_b, provides energy to resuspend sediment, the breaking angle α_b and the gradient of breaking wave height along the coast, $\partial H_b/\partial y$, determine the flux direction. Whether the beach is eroding or accreting, however, depends on the gradient of I(y), *i.g.*, $\partial I(y)/\partial y$, see Eq. 3. In this equation, the alongshore gradient of beach slope, $\partial(1/\tan \beta)/\partial y$, is assumed to be negligible small and ignored.

$$\frac{\partial I}{\partial y} \propto (H_{bx}) \frac{\partial H_{bx}}{\partial y} \left[\sin 2\alpha_b - s \frac{\partial H_b}{\partial y} \right] + H_{bx}{}^2 \left[2 \cos 2\alpha_b \frac{\partial \alpha_b}{\partial y} - s \frac{\partial^2 H_b}{\partial y^2} \right]. \tag{3}$$

where $H_{bx} = H_b \cos \alpha_b$ is the shore-normal component of wave energy, and $s = K_{\Delta H}/\tan \beta$. If H_b and α_b are constant along a coast (the straight solid line in Figure 3, then $\partial I(y)/\partial y = 0$, which indicates the shoreline will not change. For a positive $\partial I(y)/\partial y$, the beach will erode because more sediment leaves than arrives. For a negative $\partial I(y)/\partial y$, the beach will accrete because less sediment is exported than imported to an arbitrary control volume.

Although both the gradient of H_b and α_b can affect $\partial I(y)/\partial y$, the influence of H_b is more important because of the square term (see Eq. 3). Considering the difficulty to obtain accurate wave direction information using the parabolic wave models (MAA *et al.*, in press), it is suggested to use the change of breaking wave height alone in this interim stage to determine the possible influence on shoreline evolution.

In reality, when plotting the breaking wave height along a coast, one will never get the same breaking wave height along the coastline. A certain degree of modulation exists (see the dashed line in Figure 3). The larger the Breaking Height Modulation (BHM), the larger the gradient of H_b, and thus, a more severe change of shoreline.

In general, an existing shoreline usually represents some degree of balance which is the combined result of all possible wave conditions. Once the balance is disturbed, *e.g.*, wave condition changed by dredging at an offshore shoal, some degree of change on the shoreline is inevitable. In order not to affect the existing developments along the coast, an ideal dredging plan would not cause any change to the wave conditions at all. It is unrealistic, however, to expect that any dredging plan can achieve this ideal objective. In reality, one must look for an acceptable dredging plan.

In evaluating results generated by the wave transformation model, we use the original Breaking Height Modulation (BHM) as the basis (thus, a number of 1). If the change of bathymetry should amplify the modulation (see the dotted-dashed line in Figure 3), the bathymetric change would not be favorable. This is simply because more severe alteration of the shoreline would result. For a favorable change of bathymetry, the BHM should be reduced, *i.e.*, less than 1 (*e.g.*, 0.5 in Figure 3).

RESULTS AND DISCUSSION

The computational results would be described best using the calculated breaking wave height profile along the coast for the most severe sea coming from the ENE and the northeaster waves coming from the E. For the most severe sea

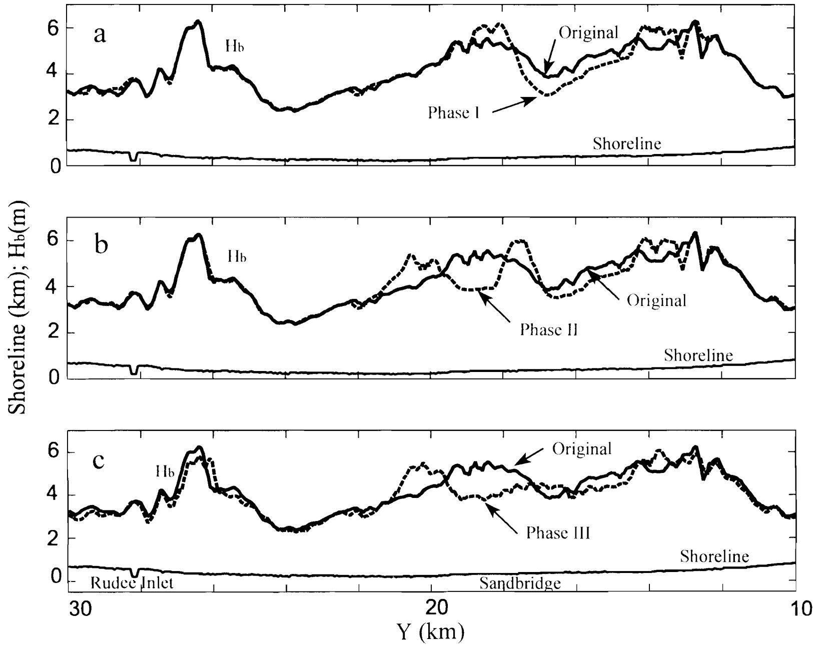

Figure 4. Comparison of Breaking wave Height Modulation (BHM) for the most severe sea coming from the ENE. (a) After completion of phase I; (b) after completion of phase II; (c) after completion of phase III.

waves coming from the ENE, the original profile of breaking wave height is given as the solid line in Figure 4a. Near the Sandbridge area (Y = 12 to 20 km), the maximum difference in breaking wave height is about 1.8 m. This number is selected as BHM = 1. After completing the first phase of dredging, the maximum difference of breaking wave height increases to about 3.2 m, which corresponds to BHM increase of 1.8 (dashed line in Figure 4a). This is not a favorable condition. After completion of Phase 2, another peak was created at x = 20 km, but the overall BHM decreases a little to 1.5 (dashed line in Figure 4b). If the dredging at Site C were completed, the BHM can be reduced to its original level, *i.e.*, BHM = 1.0 (Figure 4c). In other words, dredging at Site C is necessary for keeping the same breaking-wave modulation for the most severe sea coming from the ENE direction.

For the Northeaster waves coming from the E, the BHM increases to 3.3 after the first phase dredging (Figure 5a). This is not a favorable condition. At the completion of phase 2, the BHM decreases a little to 2.7 (Figure 5b). Only if the dredging at Site C were completed would the BHM be reduced to its original level, *i.e.*, BHM = 1.0 (Figure 5c).

The BHM for other wave conditions is summarized in Table 1. If only Phase 1 and Phase 2 dredging are considered, as originally envisioned, the changes of breaking wave height modulation for all the wave conditions are all negative (Table 1). The worst case scenario may cause more than a 300% increase in breaking wave height modulation. This means more severe shoreline change may occur. To reduce the possible impact, a third phase dredging to remove the shoal left after the first two phases of dredging is necessary. After completion of the third phase dredging, it is possible to have a positive change for the Northeaster waves (H = 1.9 m, T = 12 s) and a neutral change for the severe sea (H = 3 m and T = 14 s). For the most severe sea (H = 6.2 m and T = 20 s), a negative impact still exists for all five selected directions, from the NE to the E. The severity of these negative impacts, however, are not large except for the NE direction. In other words, if waves do not come from that direction, then the possible negative impact would still be tolerable, especially because the RCPWAVE may over-predict the wave energy modulation (MAA *et al.*, in press).

This study indicates that for the waves that can occur every year (severe sea and Northeaster waves), the revised dredging plan, if fully implemented, will not cause a negative impact to the nearby beach. Local changes, however, may still exist.

For the most severe sea, more studies to find the possible wave directions based on a reliable predictive hurricane wave hindcast model are needed for a better assessment of the possible consequences of dredging. This is because the most severe sea is possible only when a strong hurricane passes through the offshore area near Sandbridge.

Currently, this method only uses changes of breaking wave height information to evaluate the possible impact of dredging. This is because of the difficulty in obtaining accurate information on changes in breaking wave angle using parabolic wave transformation models. Although a model that solves the elliptic wave transformation equation can provide accurate wave direction information, it is not practical to use it for large study domains because of the huge computing time required. Thus, the proposed method can only be con-

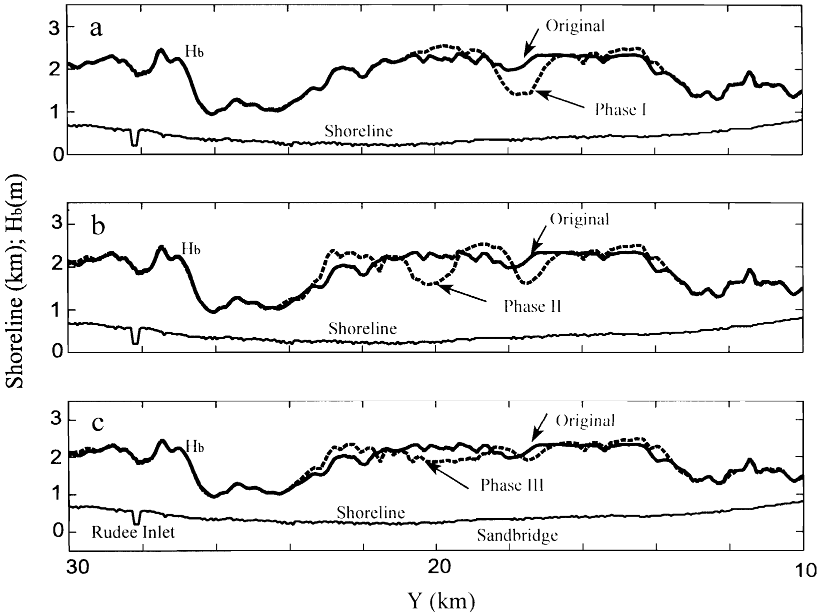

Figure 5. Comparison of Breaking wave Height Modulation (BHM) for Northeaster waves coming from the E. (a) After completion of phase I; (b) after completion of phase II; (c) after completion of phase III.

sidered as a first step towards finding a method of determining the possible man-made impact on shoreline change.

Before working on the next step of evaluation, a wave transformation model that is capable of providing accurate wave height and direction in a timely manner is needed. This is not a simple task because solving the elliptic mild slope equation for a large computation domain and realistic wave spectra requires enormous computing resources.

CONCLUSIONS

A method that yields quantitative results with which to evaluate the possible impact on the shoreline caused by man-made alterations to wave transformation processes is presented along with a case study. Although this study uses only simple harmonic waves, it demonstrates a clear and deterministic approach for the purpose of evaluating consequences of modifying bathymetry. When the Breaking wave Height Modulation (BHM) is larger than 1, more gradient of breaking wave energy may result at the shoreline and the change is considered to be unfavorable. A favorable alteration on wave transformation processes will generate a BHM that is smaller than 1.

Table 1. *Summary of the change on breaking wave height modulation.*

Wave Direction	Dredging Phase	Northeaster	Severe Sea	Most Severe Sea
NE	1	1.15	1.47	2.90
	2	1.19	1.63	2.80
	3	1.00	0.88	2.60
N63E*	1	1.45	1.42	1.59
	2	1.27	1.37	1.47
	3	0.91	1.12	1.30
ENE	1	1.90	2.07	1.86
	2	1.40	1.30	1.50
	3	0.84	1.02	1.00
N83E*	1	3.13	2.88	1.81
	2	2.00	2.90	2.43
	3	1.11	1.77	1.63
E	1	3.33	1.88	1.68
	2	2.70	1.70	1.77
	3	1.00	0.74	1.22

* N63E represents waves coming from an azimuth 63° clockwise from N.

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