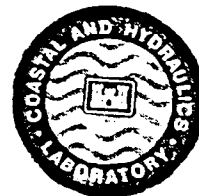




Coastal Engineering Technical Note



Depth of Closure in Beach-fill Design

By Dr. Nicholas C. Kraus, Dr. Magnus Larson and Randall A. Wise

PURPOSE

This Technical Note presents guidance on use of the depth of closure for beach fills placed on the open coast. An operational definition of the depth of closure and the associated conceptual background are presented. Procedures for estimating the depth of closure are given and illustrated with calculation examples.

INTRODUCTION

The depth of closure (DoC) affects numerous coastal engineering operations such as beach-fill design, planning of beach-profile surveys, siting and functioning of structures (including jetties, groins, breakwaters, pipelines, and wastewater outfalls), sediment-budget analysis, sand borrow-site identification, dredged-material placement in the offshore, and deployment of marine instrumentation. This note concerns the DoC for beach-fill design. It is assumed that the engineer or planner is involved in developing the design of a sand beach fill for the open coast. The fill project will have an expected number of years between renourishments, such as 3 to 10 years, or have a certain lifetime without renourishment, as might be the situation in a Section-933 project (one-time placement of fill as a beneficial use of dredged material to achieve a specified level of protection). Some of the fill placed on the beach berm and inshore in a construction cross section will gradually move offshore to the DoC as the nourished profile adjusts to changes in water level and to wave action by shifting seaward to form the design cross section. Therefore, an accurate estimate of the DoC helps form an accurate estimate of the required fill volume.

DEFINITION

The DoC has been defined in various ways, including profile pinch-off depth, critical depth, depth of active profile, depth of active (sediment) movement, maximum depth of beach erosion, seaward limit of nearshore eroding wave processes, and seaward limit of constructive wave processes. These definitions have various applicabilities but are not considered sufficiently precise for beach-fill design. In this note, the following definition is employed:

The depth of closure for a given or characteristic time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore.

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This definition is general in that it applies to the open coast where nearshore waves and wave-induced currents are the dominant sediment-transporting mechanisms, as well as to non-wave-dominated locations. Non-wave-dominated locations include: the beach adjacent to a long jetty, at which sediment may be jetted offshore by a large rip current; an ebb tidal shoal where the tidal current is a major contributor to the sediment-transporting processes; and a shoal dominated by offshore processes. Beach-fill projects are usually conducted on the open coast, in the wave-dominated nearshore environment, but the engineer should be aware that other processes may determine the DoC, depending on the circumstances. It is noted that the definition of the DoC does not include the word "erosion," because the nearshore profile can gain sand from the offshore during large storms (Larson and Kraus 1994).

Because of the multitude of alternative definitions, key elements or concepts in the above definition are now discussed. The definition of the DoC as given above contains five key elements:

- a. The definition implies that a DoC can be reliably identified.
- b. The DoC is defined as the *most landward depth* at which no significant change occurs.
- c. The definition requires an estimate of *no significant change in bottom elevation and no significant net cross-shore sediment transport*.
- d. The DoC concept contains a time frame (e.g., that related to the renourishment interval or design life of a project).
- e. At the DoC, cross-shore transport processes are effectively decoupled from transport processes occurring further offshore.

These points are discussed below.

Identification of the DoC: In a typical engineering project, the DoC will be determined either through profile surveys done over several years at fixed survey lines or through an estimation procedure such as described below. Experience in beach profile surveying and more traditional hydrographic surveying on numerous beaches in the United States and abroad indicates that a DoC can be identified and quantitatively estimated on the open coast through accurate surveying.

Most Landward Depth: Figure 1 shows the result of surveys made by sea sled on a profile survey line at the foot of 56th Street, Ocean City, Maryland, where a shore-diagonal finger shoal exists in the offshore. In this figure, the envelope of recorded elevation (above and below the mean) in any profile survey over the 4-year interval of available data and the standard deviation in depth are plotted as functions of the distance offshore. The envelopes tend to converge in the depth range of 18 to 26 ft (5.5 to 8.0 m) for this particular profile, seaward of which the profile elevations separate over the crests of the shoals. The separation in profile depth over the shoals is probably caused by the transport of sediment on the shoals and the subsequent migration of these bodies. The depth in Figure 1 is referenced to the National Geodetic Vertical Datum (NGVD).

Formation of the offshore shoals can be attributed to earlier coastal and geologic processes (McBride and Moslow 1991) and not to offshore movement of sediment from the present beach.

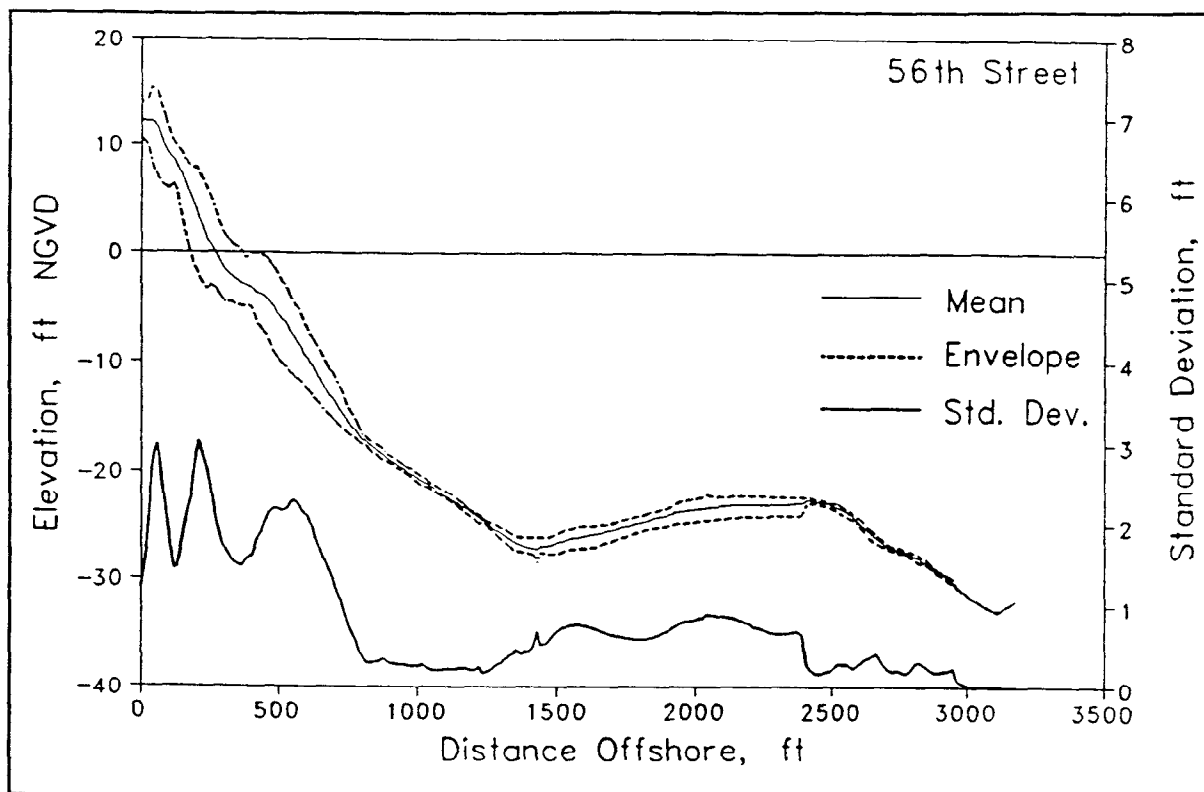


Figure 1. Mean, envelope and standard deviation of profile survey elevations, 56th Street, Ocean City, Maryland

The convergence of the profile envelope landward of the offshore shoals indicates that movement of sediment on the shoals is not directly related to sediment exchange on the nearshore profile. Such shoals, however, if located close enough to shore, would alter the refraction pattern in the nearshore and cause a systematic and persistent change in longshore sand transport at the fill, leading to “hot spots” of erosion (Stauble and Kraus 1993). The shoals might also influence nearshore processes by breaking storm waves, or by eventually moving into the nearshore over long time scales.

Because of the possibility of the appearance of multiple locations on the profile that extend above a certain depth, changes in profile elevation and net sediment transport of a certain magnitude can occur in more than one location. The requirement of “...no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore” is included in the definition to indicate that the DoC effectively separates the nearshore and beach processes from the offshore and shelf processes (at some time scale). Based on these criteria, the DoC for the profile data shown in Figure 1, and a corresponding 4-year time interval, is approximately 18 ft.

In summary, for beach-fill design at Ocean City and at other locations where net sediment

transport and bottom-elevation change may occur on shoals far from the beach, the DoC is located at the most landward depth where significant change in the nearshore profile is not observed.

“Significant”: The definition includes the term *significant*. The exact magnitude of bottom elevation change considered to be significant may vary from project to project based on the time scale of interest as well as site-specific conditions such as wave climate, sediment properties, and profile shape. In general, profile change on the order of several inches is considered significant from an engineering standpoint. The significance of profile change at a specific location may be identified through analysis of profile survey data collected over an extended period of time. As illustrated in Figure 1, a sharp decrease in the standard deviation in profile depth to a small value indicates the limit of significant profile change.

Some definitions of DoC substitute the word “measurable” for the word “significant” as used above. Because measurement variability and error will always yield some change in bottom elevation, the terminology “significant” appears more appropriate. It is the responsibility of the engineer to judge if the bottom change is actual or an artifact of measurement limitations.

At the present time, the sea sled provides the most accurate surveying method and is recommended for monitoring beach-fill projects (Grosskopf and Kraus 1993, 1994). This method has an accuracy within ± 1 in. (2.54 cm) (Birkemeier 1985; Clausner, Birkemeier, and Clark 1986). Factors limiting accuracy include deviations in horizontal position, measurement of horizontal and vertical position of the survey prism at great distance, and movement of the sea sled while surveying. The accuracy of sled surveys (order of 1 in. (2.54 cm)) is adequate for identifying significant profile change defined on the order of several inches.

Sediment transport is not typically measured in the offshore, and so it must be inferred from profile survey measurements, or, possibly, from grain size analysis and change in sediment color (*Shore Protection Manual* 1984, Smith 1995). If several inches of different (new) sediments overlay older sediments, the DoC may not have been reached for the subject time interval, a storm with wave heights exceeding the return period of the subject time interval may have occurred, or other, unanticipated processes may have been acting (warranting reexamination of the data or the site).

Time: For engineering applications, such as beach-fill design, beach profile change must be considered at several time and space scales ranging from days to decades (Larson and Kraus 1994, 1995). To illustrate the time dependence in profile change, Figure 2 plots average absolute depth change between consecutive surveys with profile elevation at WES’s Field Research Facility (FRF) located at Duck, North Carolina, for the winter months of January through March and the summer months of July through September for the 11-year interval 1981-1991 (profile surveys conducted approximately every two weeks). In this figure, negative elevation values denote depth, and positive values denote elevation above NGVD, which is almost equal to mean sea level at Duck. Values in the figure were calculated from 340 profile surveys taken with the Coastal Research Amphibious Buggy (CRAB). The mean absolute depth change decreases to about

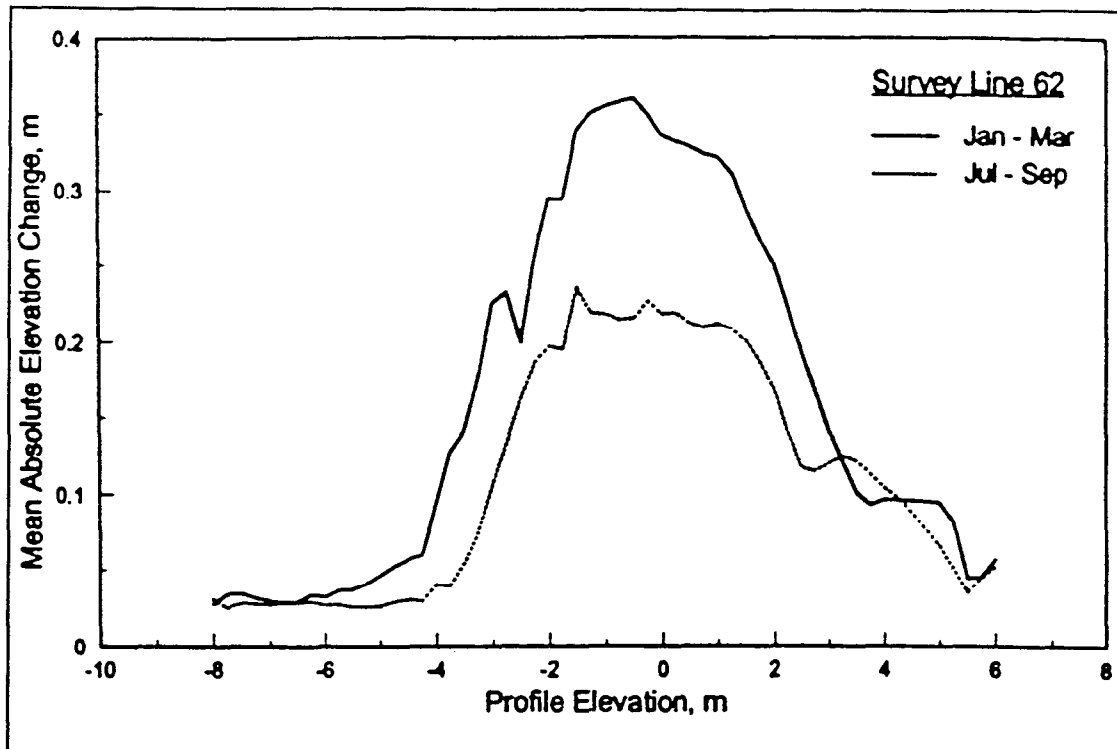


Figure 2. Mean absolute elevation change, FRF Survey line 62, Duck, North Carolina

2.5 cm at approximately the 4-m depth in the summer, whereas the mean absolute depth change reaches the 2.5-cm value at the 6-m depth in winter.

For the 11-year interval, the mean significant wave height and mean yearly maximum significant wave height were 1.28 and 3.4 m for winter and 0.88 and 2.2 m for summer, with the mean wave period for both seasons essentially unchanged at about 8.4 sec. The DoC is seen to be primarily dependent on wave height occurring over a certain time interval and season, as first pointed out by Hallermeier (1978, 1981) and discussed in estimation procedures below. The DoC should, therefore, be associated with a specified time interval. For the case of Duck, North Carolina, it is concluded that the decade-long DoC is about 6 m NGVD.

Decoupling of Nearshore and Offshore Processes: It is well-known that sediment can move at appreciable depths. For example, Komar, Neudeck, and Kulm (1972) found changes in ripples on the sea bottom at more than the 100-m depth. Artifacts from sunken ships in the deep sea that have been photographed or recovered show evidence of abrasion by moving sediment. The question of coastal-engineering interest is whether sediment-transport processes in the far offshore influence the functioning of a beach fill. The answer depends on the lifetime of the project; i.e., the appropriate time scale, and the location where the offshore transport is occurring. In any case, the engineer must not confuse nearshore processes that control sediment movement at the beach with processes occurring far offshore, which are usually not related to time scales of beach-fill projects.

ESTIMATION OF THE DoC: In applications to beach-fill design, the DoC is required to estimate the volume of sand needed to be placed on the beach profile. A typical design consists of a dune (to mitigate damage from storm inundation, waves, and erosion) and a berm to protect the dune. The longevity of the berm is controlled by the historical shoreline-erosion rate and end loss or transition effects (typically longshore transport processes), as well as by adjustment of the filled profile to achieve equilibrium (a cross-shore transport process). The DoC enters in calculating the volume per unit length alongshore needed to be placed to provide a certain minimum berm width over a certain time period.

DoC and the Vertical Datum: The DoC is a water depth measured from some datum (for example, NGVD) and the change in beach volume includes the total vertical distance of the berm height plus the DoC. It is important to remember that NGVD is not a tidal datum, and NGVD does not bear a constant offset to any particular tidal datum along the coast. Rather, such a relation is location-specific. Tidal datums and their relation to NGVD may be obtained from the National Ocean Service of the National Oceanic and Atmospheric Administration. Predictive equations for the DoC (e.g., Hallermeier 1978, 1981; Birkemeier 1985) employ the tidal datum mean low water (MLW) as a reference datum. Because Corps of Engineers design is often performed with NGVD as the datum, a conversion must be made between MLW and NGVD, as shown in the examples below.

Volumetric Rule of Thumb: A fundamental assumption is that over periods of years the overall form of the profile is preserved (for similar grain sizes) under the process causing the change in the profile, as shown in Figure 3. The two common ways of calculating profile change under such an equilibrium profile assumption are (a) translate a design profile seaward, which may include bars, or (b) assume an idealized profile shape. The concept of DoC is implicit in a rule of thumb introduced by early U.S. coastal engineers, which states "the loss or gain of one square foot of beach berm equals one cubic yard of erosion or accretion." This rule implies a long-term DoC somewhat less than 27 ft, depending on the elevation of the beach where the material was lost. In metric units, the rule of thumb is: loss or gain of 1 sq m of beach berm equals 8.2 cu m of loss or gain. (For conversion to metric units, 1 ft = 0.3048 m, and 1 cu yd = 27 cu ft = 0.765 cu m).

Predictive Formulas: In the absence of beach profile survey measurements or geological indicators pertinent to beach-fill design, mathematical formulas are used which relate the DoC to properties of the incident waves.

Hallermeier (1978, 1981) related the DoC to the critical value of a Froude number Fr describing the threshold of erosive sandbed agitation by wave action

$$Fr = \frac{U_b^2}{\gamma'gd} = 0.03 \quad (1)$$

in which U_b is maximum horizontal wave-induced fluid velocity at water depth d , g is acceleration

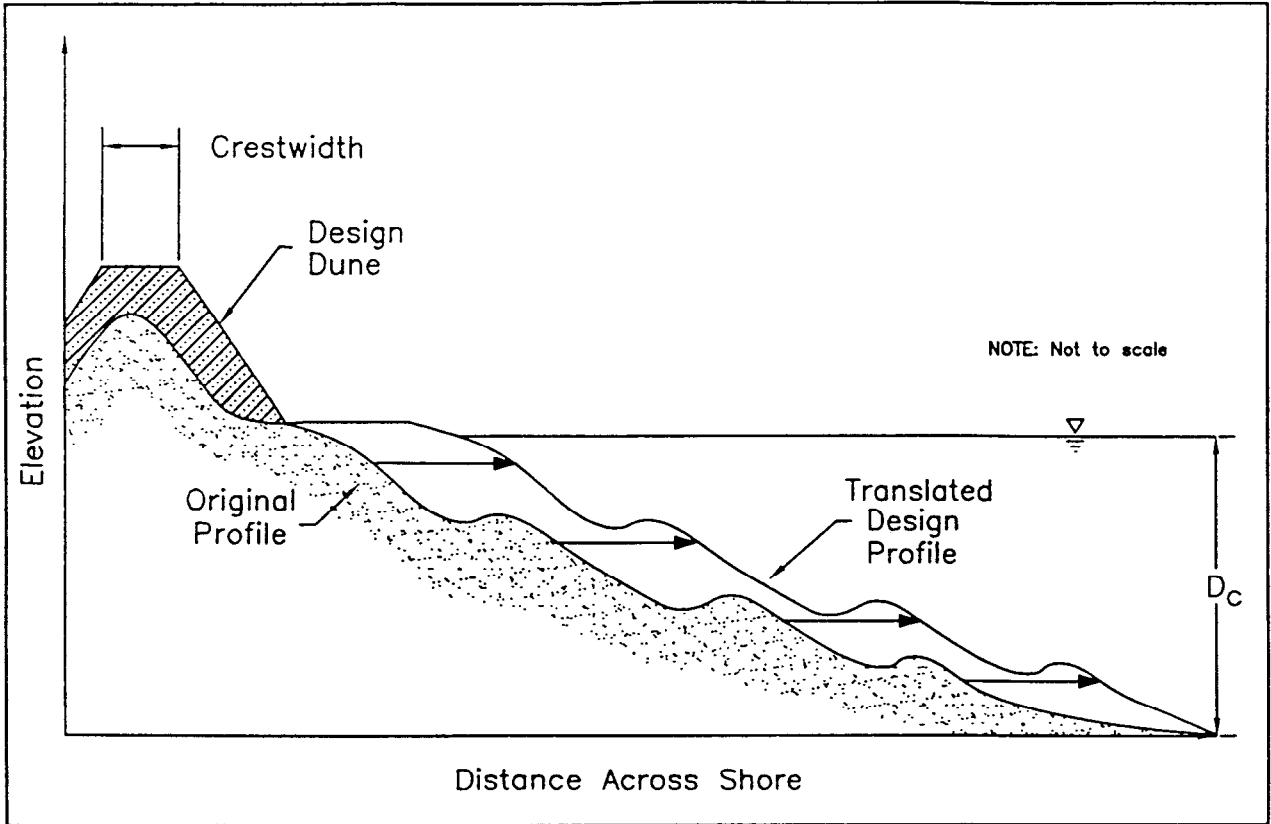


Figure 3. Translation of profile form

of gravity, and γ' is the ratio of the difference in density between sediment and fluid to the fluid density. Using linear wave theory and a value of $\gamma' = 1.6$ for quartz sand in seawater, Hallermeier expressed Equation 1 in the form of a predictive equation for the DoC

$$D_c = 2.28H_s - 68.5 \left(\frac{H_s^2}{gT^2} \right), \quad \text{MLW} \quad (2)$$

in which D_c is the symbol for the DoC, H_s is local significant wave height exceeded 12 hr in a particular time interval (discussed further below), and T is the wave period associated with H_s . Hallermeier (1978, 1981) validated Equation 2 with laboratory and field data and found that the DoC was insensitive to sediment grain size for sizes in the typical range found in the nearshore of sandy beaches (0.16 to 0.42 mm). The first term in the Hallermeier equation is directly proportional to wave height and is the main contributor to the predicted value of the DoC. The second term provides a small correction associated with the wave steepness.

Birkemeier (1985) modified the Hallermeier equation to $D_c = 1.75H_s - 57.9(H_s^2/gT^2)$ with a

site-specific adjustment of the coefficients based on visual estimates of profile pinch-off observed in profile survey data for 10 pairs of surveys conducted at Duck, North Carolina. The Birkemeier equation produces a smaller estimate of the depth of closure than the Hallermeier equation for given wave conditions.

Houston (1995) simplified Birkemeier's formulation using properties of a Pierson-Moskowitz wave spectrum (Rijkswaterstaat 1986) and a modified exponential distribution of significant wave height over time to express the DoC in terms of mean annual significant wave height $\overline{H}_s$ according to $D_c = 6.75 \overline{H}_s$. Following Houston's approach, the Hallermeier equation can similarly be expressed in the form

$$D_c = 8.9 \overline{H}_s, \quad \text{MLW} \quad (3)$$

Equation 3 has the advantage of requiring only a single parameter to estimate DoC without the need to determine the wave height and period exceeded 12 hr in a particular time interval. However, Equation 3 is not applicable for estimating DoC for a particular storm event as discussed below.

In the original formulation of Hallermeier (1981) and subsequent modifications, the DoC was defined based on the largest wave height exceeded 12 hr per year. This definition incorporates a time element, but the exact event associated with the value of wave height is ambiguous. Depending on changes in storm activity and wave conditions from year to year, the predicted DoC can vary substantially. In order to determine a representative value of the DoC based on this definition, wave conditions averaged over a period of several years must be employed.

A useful extension of calculating the DoC based on average annual wave conditions is to relate the DoC to a particular time period of interest over which specific storm events or seasonal wave conditions occur. A similar "wave-by-wave" interpretation of the DoC was introduced by Kraus and Harikai (1983) in shoreline change simulation modeling. In a wave-by-wave or event approach, the DoC can be associated with a *recurrence frequency* or return period for a particular storm. The return period should be associated with the wave height, not with the storm surge. Such information is normally generated for a beach-fill design during project study.

DESIGN RECOMMENDATIONS: If available, data from beach profile surveys at the project site or a neighboring location should be employed to determine the DoC for beach-fill design. The envelope of profile change measured over a given time interval provides an accurate estimate of the DoC associated with wave conditions occurring during the interval. Also, morphologic features observed on beach profiles (such as remnant storm bars and active inner bars) can give an indication of the DoC for different time scales.

In the absence of profile data, Equation 2 (the Hallermeier equation) is recommended as the primary calculation method for estimating the DoC, because it provides a more conservative estimate for design. Conservative prediction of the DoC by the Hallermeier equation is confirmed by Nicholls, Birkemeier, and Hallermeier (1996), who show that the formulation provides an

upper bound to the scatter in measurements of DoC at Duck, North Carolina. Example 1 given below similarly shows that Equation 2 provides an upper bound estimate of DoC at Ocean City, Maryland.

Equation 2 can be applied using either a wave record of given length of time or a single storm event of given wave height return period. To estimate the DoC for a given wave record, the significant wave height and associated period exceeded for 12 *consecutive* hours within the record is employed. For example, the DoC for a given 3-year wave record would be estimated using the largest significant wave height exceeded for 12 consecutive hours over the entire 3-year interval. Equation 2 can also be applied using an event-based approach to determine the DoC associated with a recurrence frequency or return period for a particular storm. In this case, the 12-hr significant wave height used to calculate the DoC would be determined from the storm of interest (e.g., a storm characterized by a wave height return period of 10 years).

It is noted that the alternative applications of Equation 2 described above (length of record versus specific event) may not produce the same value of DoC for the same time interval of data. For example, if in a given 5-year record of wave data, an extreme event occurred with a wave height return period of 20 years, the resulting DoC would have an associated return period of 5 years based on the length of wave record, and a return period of 20 years based on recurrence frequency of the storm event. To determine an accurate estimate of the DoC for a particular (*n*-year) return period using wave records rather than individual ranked storms, an average value should be calculated using multiple *n*-year wave records.

Equation 3 provides a simple method for estimating the average annual DoC, but cannot be applied on an event basis. Also, the assumed wave height distribution employed in the derivation of Equation 3 may not be applicable to all wave climates or over specific time scales of interest. Equation 3 is recommended for use only as a preliminary estimate of DoC or if wave information required by Equation 2 is not available.

In application of either of the predictive formulas, the input wave height should be determined at a nearshore location (approximately 10-m depth) to satisfy the local wave height assumption of the calculation methods. Wave information from offshore locations (such as from an offshore wave gauge or hindcast station) should be transformed to a nearshore depth using a wave transformation technique such as WAVETAN (Jensen 1983, Gravens and Hanson 1991). Use of offshore wave information alone will produce erroneously high estimates of the DoC.

In estimating DoC for beach-fill design, various time scales must be considered. A DoC based on a time scale on the order of a typical renourishment interval (approximately 5 years) is recommended for use in determining volume requirements of the design project. Designing a project based on a long-term DoC on the order of the project life (e.g., 50 years) is an overly conservative approach that may not be cost-effective due to the large initial construction volume required to nourish out to the great depth. However, additional volume requirements associated with the long-term DoC for extreme events should be accounted for in the overall design such as by inclusion in emergency maintenance provision or prorating over the renourishment schedule.

It is noted that selecting a design project based on a short-term DoC does not imply that the project provides inadequate protection against extreme events. Storm erosion and inundation impacts are accounted for in the beach fill design process by evaluating response of the design profile to storms of varying intensity. Because the design profile, which extends out to the design DoC, is used as an initial condition in evaluating storm-induced erosion and flooding, the impacts of sediment being transported beyond the design DoC during extreme storms will be accounted for in assessment of storm protection provided by the project. Thus, if a storm occurs which is more severe than the event associated with the design DoC, the project should provide the expected amount of storm protection. However, following the storm, additional volume will be required to restore the berm width back to project design specifications, since material will have been moved beyond the design DoC. The amount of additional volume required, in this case, could be estimated by comparing the design DoC with the DoC of the event in question.

Example 1: Comparison with Data - Ocean City, Maryland. The beach fill at Ocean City, Maryland, has been extensively examined in the literature (e.g., Kraus and Wise 1993, Stauble and Kraus 1993) because considerable monitoring data are available for this site (Stauble et al. 1992). During the particularly stormy 3-1/2-year period from August 1988 to January 1992, data were compiled from a nearshore wave gauge located at a depth of approximately 10 m. The wave height exceeded for 12 hr during the period was 9.8 ft (3.0 m) with an associated wave period of 10.2 sec (occurring during the January 1992 storm). Substituting these values into Equation 2 gives $D_c = 20.4$ ft (6.2 m) MLW or 22.0 ft (6.7 m) NGVD (MLW lies 1.6 ft (0.5 m) below NGVD at Ocean City, Maryland). The average of the significant wave heights measured at the gauge during the period was 2.1 ft (0.6 m). Substituting this value into Equation 3 gives $D_c = 18.7$ ft (5.7 m) MLW (20.3 ft (6.2 m) NGVD).

Stauble et al. (1992) determined the DoC at Ocean City over the same period by examining profile survey data from 12 survey lines. Results of the analysis indicated a DoC ranging from 16 to 22 ft (4.9 to 6.7 m) NGVD for individual profiles, with 20 ft (6.1 m) NGVD being a representative value for all profiles. Thus, Equation 2 accurately predicts the upper bound of the measured DoC for this data set, whereas Equation 3 predicts a lower value equal to the representative DoC for all profiles.

Example 2: Project Design - South Padre Island, Texas. Hurricane and tropical storm wave heights and periods for different recurrence intervals were generated for a beach-fill project at South Padre Island, Texas. The site faces the Gulf of Mexico and is exposed to relatively frequent hurricanes. Table 1 shows the 12-hr significant wave height and wave period for varying storm wave height return periods. Equation 2 gives the results in the fourth column referenced to MLW and in the fifth column adjusted to NGVD at South Padre Island.

These results indicate that, at this hurricane-prone location, it is probably more economical to construct a narrower berm designed for shorter return periods together with a dune to protect against catastrophic flooding and erosion associated with extreme events, as opposed to constructing a wide berm designed for long return periods. The relatively large depth of closure associated with long return periods would require a large volume of fill material to maintain a

wide berm. Also, placement of a large quantity of material deeper than about 25 ft (7.6 m) NGVD

Table 1 Estimated Depth of Closure for South Padre Island, Texas								
Storm Return Period, year	Wave Height		Wave Period sec	Depth of Closure			Depth of Closure	
	ft			m	ft (MLW)	m	ft (NGVD)	m
10	11.4	3.5	10	23.2		7.1	23.6	7.2
20	14.2	4.3	11	28.8		8.8	29.2	8.9
50	17.3	5.3	12	35.0		10.7	35.4	10.8
Note: For South Padre Island, NOS data at Port Isabel give the relation NGVD = MLW + 0.44 ft (1966 adjustment to NGVD)								

would allow bypassing of material at the jetty to the south of the beach and increase the rate of infilling at the Brazes-Santiago navigation channel.

ADDITIONAL INFORMATION: Related Notes are: CETN VI-5, "Guidelines for Planning Beach Surveys;" CETN II-3 1, "Guidelines for Surveying Beach Nourishment Projects;" and CETN B-32, "Beach-Fill Volume Required to Produce Specified Dry Beach Width." This note was prepared by Dr. Nicholas C. Kraus, U.S. Army Engineer Waterways Experiment Station (WES), Coastal and Hydraulics Laboratory (CHL); Dr. Magnus Larson, University of Lund (Sweden), and Mr. Randall A. Wise, CHL. For further information, please contact Dr. Julie Rosati, Julie.D.Rosati@erdc.usace.army.mil

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