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Calculating Depth of Closure Using WIS Hindcast Data

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PURPOSE: In this Coastal and Hydraulics Engineering Technical Note (CHETN), a depth of closure (DOC) analysis for all of the United States coastlines is presented. The DOC is calculated using Wave Information Study (WIS) hindcast stations along the United States coastlines. The results summarized in this CHETN are available in the form of a spreadsheet on the Coastal Inlets Research Program (CIRP) website (*http://cirp.usace.army.mil/products/depth-of-closure.php*) and are planned to be the initial phase of a larger effort to provide DOC estimates as a publicly available interactive web tool that will also include estimates of sediment mobility. The tool will describe the theoretical boundaries of wave-initiated sediment motion for the United States using a simplified method that does not require numerical modeling of waves as well as the frequency of mobility of sediment placed in the nearshore. The tool can be used to rapidly develop a better understanding of what depth and geographical location sediment may be beneficially placed. For navigation channels the DOC would signal the location where channel infilling would lessen. This tool will be useful for any coastal engineering analysis that requires an understanding of the seaward extent of significant net sediment transport in a region.

BACKGROUND: The DOC is a useful concept for coastal engineering in nearshore regions. It is a specified depth along a beach profile where net sediment transport is very small or nonexistent, dependent on wave height and period, and occasionally, sediment grain size. More specifically, Kraus et al. (1998) state that 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." The DOC is often thought of as the location at which beach profile elevations converge through time. The first theoretical definition of DOC came from a study by Hallermeier (1978, 1981) using wave tank and field data. Initially, the DOC was related to the critical value of a Froude number describing the threshold of erosive sand bed agitation by wave action (Hallermeier 1978; Kraus et al. 1998). From the data, two zones were defined as the Inner and Outer DOCs. The Inner DOC marks the seaward extent of the littoral zone, which is characterized by increased bed stresses and sediment transport due to waves near breaking and fluid circulation (Hallermeier 1978). The Outer DOC is the seaward limit of the offshore zone, where wave shoaling is the dominant process and bed agitation remains relatively moderate (Hallermeier 1978). Birkemeier (1985) later revised the Hallermeier (1978, 1981) equations using data from the Duck, NC, U.S. Army Corps of Engineers (USACE) Field Research Facility. Many studies have been done to further verify or apply the concept of DOC (e.g., Kraus and Harikai 1983; Birkemeier 1985; Nicholls et al. 1996; Nicholls et al. 1998; Kraus et al. 1998; Wang and Davis 1999). Specific methods used to calculate DOC for this study are discussed in detail in the following section.

The concept of DOC is applied quite often in the coastal sciences, including estimating coastal sediment budgets, numerical modeling of coastal geomorphological change, and beach nourishment design (Nicholls et al. 1996). One application of this tool is the calculation of the Inner and Outer DOCs for use in designing and constructing nearshore berm nourishments. Nearshore berm nourishments are the placement of sediment in the nearshore. Berms may be active or stable based on whether or not sediment moves following placement (McLellan and Kraus 1991; Hands and Allison 1991). Active berms are those that show movement within the first weeks to months while stable berms are those that remain at the placement site and retain the same volume for years while potentially attenuating high wave energy depending on depth of placement. The Hands and Allison (1991) empirically based guidance on where to place a berm is often applied in the absence of a full numerical modeling study. Based on Hallermeier (1981) Inner and Outer DOCs, Hands and Allison (1991) defined whether 11 previously placed berms would be categorized as active or stable. Berms that were placed shallower than the Inner DOC (i.e., in the littoral zone) were always active while berms placed deeper than the Outer DOC were always stable. If a berm was placed 50% shallower than the Outer DOC, the berm was also found to be active (Figure 1) but to significantly varying degrees.

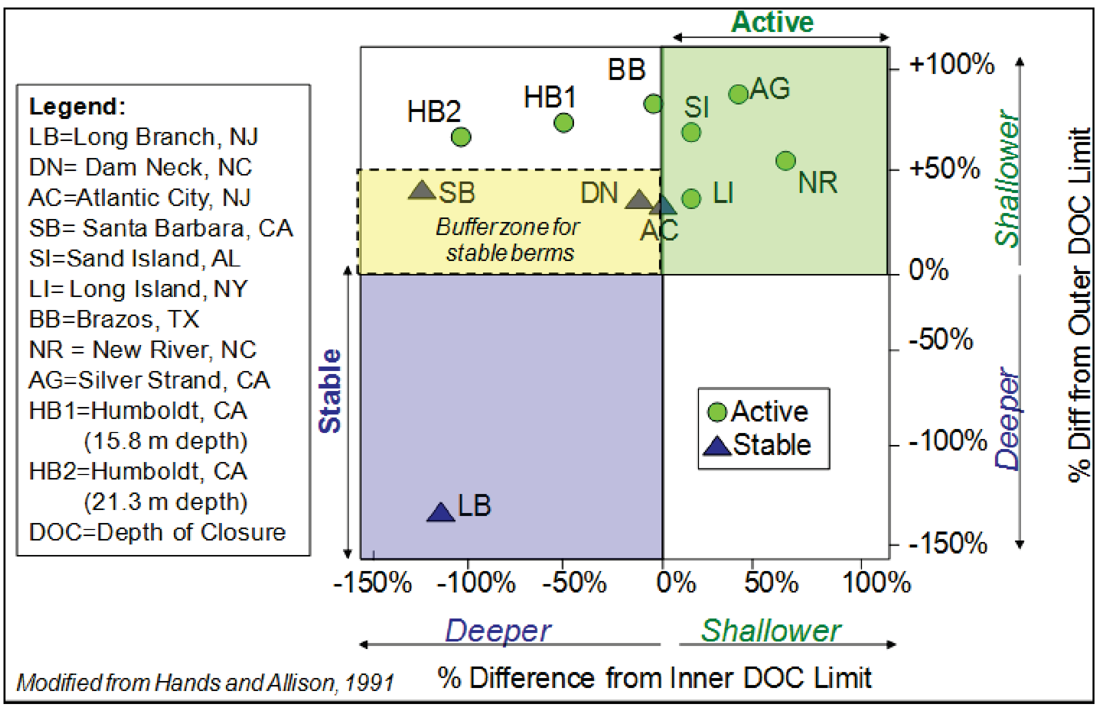

Figure 1. Placement depths for active and stable berms (from Beck et al. 2012; modified from Hands and Allison 1991).

Several methods were used to calculate the DOC along the coasts of the United States including Hallermeier (1978, 1981) and two equations from Birkemeier (1985) and are outlined in the following section.

EXISTING METHODS TO CALCULATE DEPTH OF CLOSURE (DOC): Several equations exist to calculate the DOC for a region (e.g., Hallermeier 1978, 1981; Birkemeier 1985; Nicholls et al. 1996). Using wave tank and field data, Hallermeier (1978, 1981) provided the first effective approach to calculating the seaward limit of sediment transport. The inner limit marks the seaward extent of the littoral zone where the bed experiences extreme activity caused by waves breaking and their related currents. The outer limit denotes the limit of the shoal zone where waves will cause little sediment transport and waves have neither a strong nor negligible effect on the bed (Hallermeier 1981). Based on correlations with the Shields parameter and the assumption that only the highest waves cause erosion on the beach out to the DOC, Hallermeier (1978) defined the Inner DOC as

$$d_l = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right) \tag{1}$$

where H_e is the effective wave height, or wave conditions that exceeded only 12 hours out of a single year (or the greatest 0.137% waves in a year), T_e is the associated wave period, and g is the acceleration due to gravity. H_e can be defined as

$$H_e = \bar{H}_s + 5.6\sigma_s \tag{2}$$

where $\bar{H}_s$ is the annual mean significant wave height, and σ_s is the associated standard deviation of the significant wave height (Hallermeier 1978). Based on this relationship, Hallermeier defined another equation for the inner limit as

$$d_l = 2\bar{H}_s + 11\sigma_s \tag{3}$$

The outer limit includes a grain size term, D, or d_{50}, and is defined as

$$d_i = \left(\bar{H}_s - 0.3\sigma_s\right)\bar{T}_s\left(\frac{g}{5000D}\right)^{0.5} \tag{4}$$

where $\bar{T}_s$ is the average period associated with average significant wave height. The term $\bar{H}_s - 0.3\sigma_s$ in Equation 4 is also defined as H_{sm}, or the yearly median significant wave height.

Using data from the USACE Field Research Facility in Duck, NC, Birkemeier (1985) evaluated Hallermeier's relationship for the Inner DOC. From the data, he found that a better approximation for the Inner DOC to be

$$d_l = 1.75H_e - 57.9\left(\frac{H_e^2}{gT_e^2}\right) \tag{5}$$

which can be further simplified as (Birkemeier 1985; USACE 2002)

$$d_l = 1.57H_e \tag{6}$$

Equations 1, 3, 4, 5, and 6 were used to calculate DOC in the web application tool.

METHODS: In order to calculate the DOC along all of the coastlines of the United States, hindcast data were downloaded from the USACE Wave Information Study (WIS) stations using an automated script. For each chosen station, all of the available WIS hindcast data were used to calculate the DOC. For most stations, data spanned a total of 20 years; however, some stations, such as those in the Great Lakes and Gulf of Mexico, included an additional 10–12 years. In most cases, the depths at the WIS stations are deeper than the DOC. As waves shoal, their wavelength decreases, and the wave height increases as they slow down; therefore, Snell's Law (assuming straight and parallel contours) was used to shoal each wave to a uniform depth for each coastline. Uniform depths were chosen as depths offshore of typical historical placement locations inside of which most berms might be located (Table 1) and allowed for direct comparison of DOC values when mapping. If a WIS station was shallower than the uniform depth, then no transformation was applied.

Table 1. Uniform depths chosen for each coastline used in the Snell wave propagation calculation.

Coastline	Depth, meters (m)
Pacific	15.2 m (50 ft)
Atlantic	12.2 m (40 ft)
Gulf	9.1 m (30 ft)
Great Lakes	9.1 m (30 ft)

Once the waves were shoaled towards the shoreline, several statistical wave parameters were calculated. H_e was calculated by averaging the highest 0.137% waves during each year, as well as using Equation 2. Mean H_s was calculated by averaging all of the WIS waves for each year at each station, and the standard deviation associated with the average was also calculated. Median wave heights were calculated in two ways: the first by standard statistical analysis and the second by using the previously described equation $H_{sm} = \bar{H}_s - 0.3\sigma_s$. Wave periods associated with all of the different statistical wave heights were also calculated. Once these parameters were determined, Inner and Outer DOCs were calculated using Hallermeier (1981) (Equations 1 and 4) as well as by using Birkemeier (1985) (Equation 5) and revised Birkemeier (Equation 6). Although many statistical wave parameters will be available to the user in the final version of the DOC products, as defined by Hallermeier (1978, 1981), only the wave conditions that exceeded 12 hours out of a year were used to calculate the Inner DOC while H_s was used to calculate the Outer DOC. DOCs were calculated for each year of the record, as well as by using the entire record, as suggested by Kraus et al. (1998). The Hallermeier Outer DOC limits were calculated using three different representative grain sizes (D): 0.15 millimeters (mm), 0.2 mm, and 0.3 mm. The range in median grain sizes considered provides a range in DOC depths calculated. Profiles extending from the WIS station to the shoreline were created, and intersections between the profile line and bathymetric contours were extracted. Approximate locations of specified DOCs were found by interpolating along the profile line between the extracted contour points and associated with a latitude and longitude. DOC values were organized and put into maps to illustrate trends across the United States as well as to compare the various calculation methods that were used. Hindcast wave data were organized into a series of histograms that can be created using the available data.

RESULTS: The following results discuss some examples of overall DOC trends, DOC calculated zones, and statistical wave information that will be available to the user.

Overall Trends. Overall DOC trends along the United States coastlines can be observed using the data output by the tool for each calculation method. Figure 2 shows an example of the Hallermeier Inner DOC calculated using all 20 years of data in the Gulf of Mexico and along the southeast coast. Along the eastern portion of the Gulf, DOCs are up to approximately 3 m while along the western portion, DOCs can be up to approximately 8 m. The Florida Gulf Coast experiences shallower DOCs than the Atlantic coast due to the relatively wide, flat continental shelf as compared to the narrower, deeper continental shelf on the Atlantic Coast. Along the Atlantic Coast, Hallermeier Inner DOCs can be up to approximately 11 m.

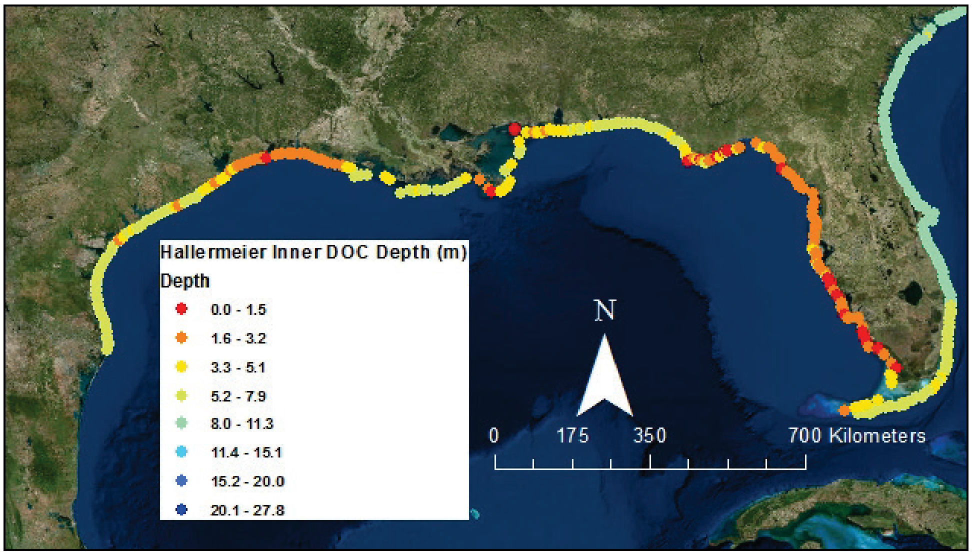

Figure 2. Example showing overall Hallermeier Inner DOC trends along the Gulf of Mexico and Southern Atlantic coasts.

Calculated Zones. Yearly DOCs for each calculation method were also determined using the WIS station's information. Currently, the data are available in tabular form. The calculated DOCs for individual years allows the user to view the minimum, maximum, and mode of DOC for a location and to gain perspective of the spatial variance of DOC in the cross-shore for each coastal WIS station. An example is shown in Figure 3. The range of depths allows the user to identify yearly trends at each station. For example, along the north western peninsular and Keys portions of Florida, the range of the different Hallermeier Inner DOCs is much larger than along the Atlantic and Panhandle Gulf coasts. It will provide the engineer or planner with an improved understanding of the variability in potential for mobility and aid in determining an appropriate DOC for their project. Understanding that in some years storm events may increase the DOC above the average may be useful in indicating the maximum volume of material that might be mobilized and thus considered *active* and can be identified as beneficial use to a shore nourishment from its placement site, where using the 20-year average might reduce the estimated volume of material available for nourishment.

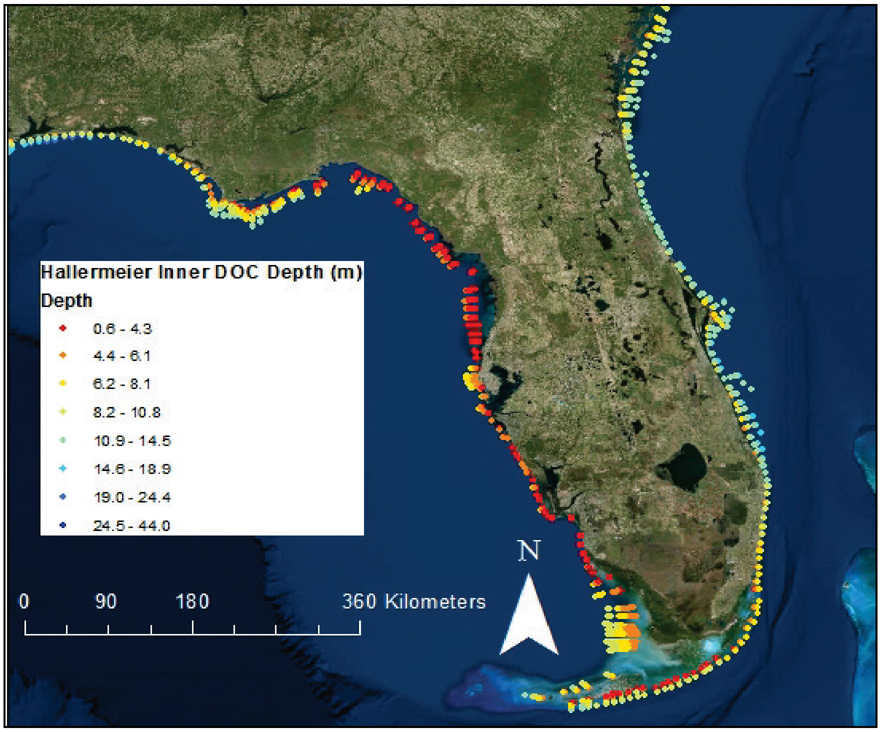

Figure 3. Example of Hallermeier Inner DOCs using WIS hindcast dataset.

The approximated locations of the DOCs along a cross-shore profile allow the user to measure the offshore distance of the depth and visualize the regional trend of the spatial location of the DOCs for an area. The locations of DOCs also aid in preliminary project design and in communication with resource agencies. For example, in Figure 3, it can be seen that DOCs along the west central portion of Florida are generally much closer to the shoreline than those on the east central portion of Florida.

Wave Statistics. Several different wave statistical parameters were calculated including H_e (calculated using Equation 2), H_{e_poe} (calculated using percent of exceedance method), H_s, H_{s_median}, H_{sm}, H_{std} (sigma), H_{s_max}, and H_{s_min} as well as their associated wave periods. These statistics are useful in determining wave climate for a particular study area. Currently, the data are available in tabular form. Figure 4 shows an example of a particular WIS station located in the western Gulf of Mexico. Yearly H_e data are reported in a histogram, and it is clear that the most frequent waves are within the 4 m range.

Overall coastal trends can also be observed by combining all of the data into one histogram. For example, Figure 5 shows a histogram of yearly H_e for the entire Gulf of Mexico coastline. In this particular case, the dominant annual wave height is less definitive and can be described by a range within approximately 2–4 m.

Finally, total H_e data (i.e., H_e calculated using all 33 years of data, rather than the individual year) are available for particular WIS stations as well as an entire coastline. Figure 6 shows an example of the total H_e data for the Gulf of Mexico. In this case, the most frequent waves were in the 2–4.5 m range.

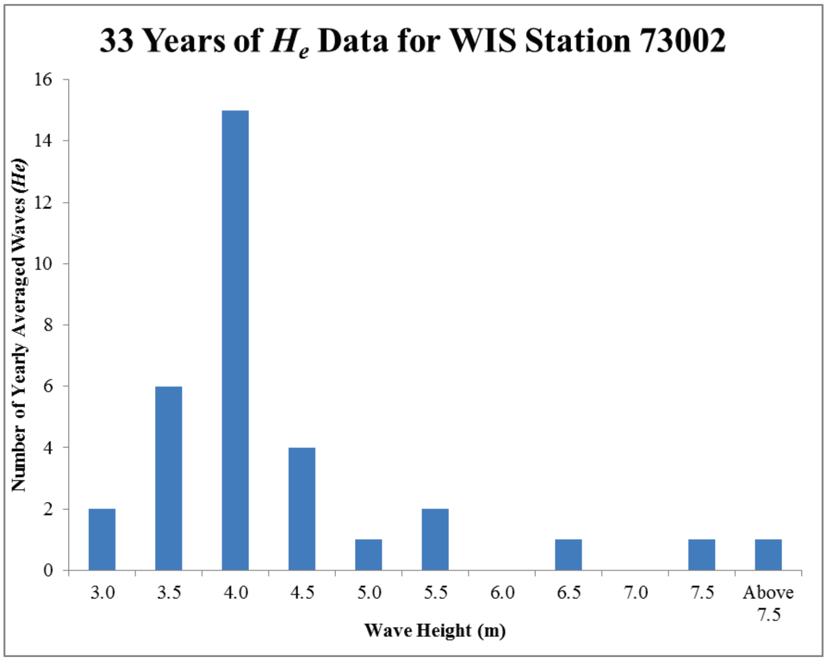

Figure 4. Example histogram of 33 years of yearly averaged effective wave heights (H_e) for WIS station 73002 located in the Gulf of Mexico.

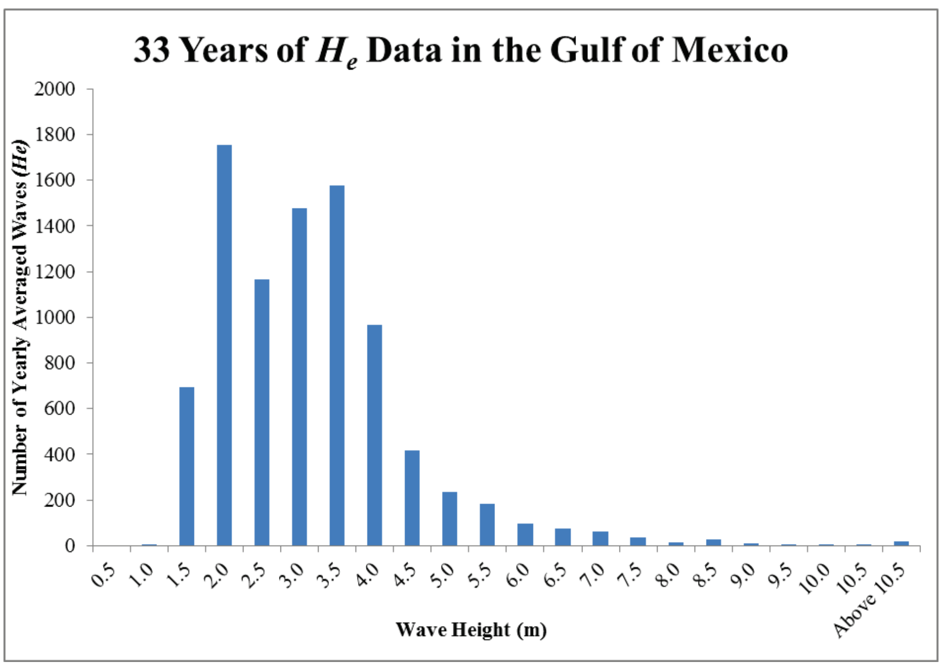

Figure 5. Example histogram of 33 years of yearly averaged effective wave heights (H_e) for the entire Gulf of Mexico coastline.

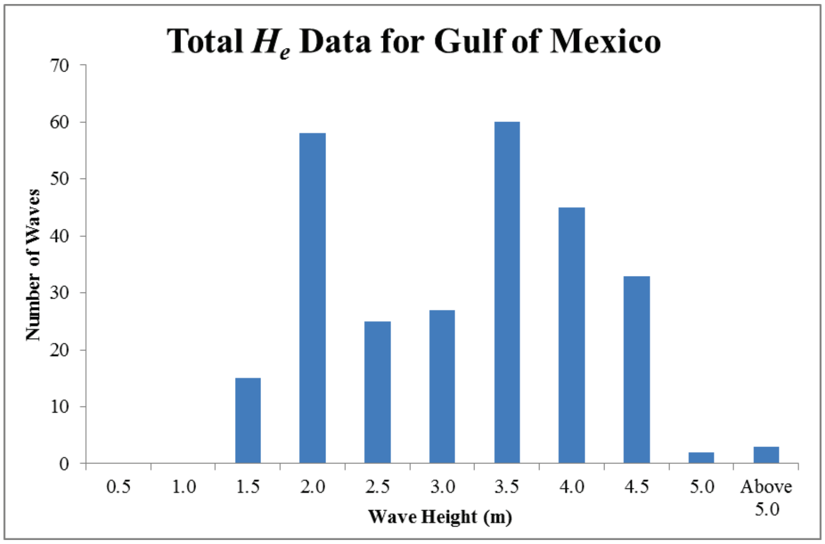

Figure 6. Example of a total H_e histogram for the entire Gulf of Mexico coastline.

Potential Applications of DOC Data. The data summarized herein and available for use are applicable in many coastal and navigation engineering projects. A specific application of these datasets is to improve the planning-level selection process for suitable locations for nearshore placement. The tool will provide easy access to this data and will give users DOCs and estimated frequency of sediment mobility based on a large dataset. Sediment mobility is calculated based on the methods in McFall et al. (in preparation). Currently, the DOC and wave statistics data are available on the CIRP website (*http://cirp.usace.army.mil/products/depth-of-closure.php*).

SUMMARY: This CHETN summarizes the calculation of the DOCs and several statistical wave parameters for the entire United States using several different equations, specifically those found in Hallermeier (1978, 1981) and Birkemeier (1985). Calculated DOCs and statistical wave parameters are available in a static spreadsheet version using preselected project location and will be available in an interactive web tool so that users may choose not only multiple project locations and WIS stations but site-specific characteristics such as grain size. This tool serves as a valuable planning level map for coastal engineers, planners, and scientists working on coastal projects.

POINTS OF CONTACT: This Coastal and Hydraulics Engineering Technical Note (CHETN) was prepared as part of the USACE Coastal Inlets Research Program (CIRP) and the Regional Sediment Management Program (RSM) by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS. Additional information pertaining to the CIRP Program may be obtained from the CIRP website (*http://cirp.usace.army.mil*) or from the CIRP Program Manager, Dr. Julie D. Rosati (*Julie.D.Rosati@usace.army.mil*). Additional information regarding the RSM Program may be obtained from the RSM website (*http://rsm.usace.army.mil*) or from the RSM Program Manager, Linda S. Lillycrop (*Linda.S.Lillycrop@usace.army.mil*). Questions regarding this CHETN can be addressed to Katherine Brutsché (601-634-4174; *Katherine.E.Brutsche@usace.army.mil*) at ERDC. This document can be referenced as

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