CHAPTER 299

APPLICATION OF THE DEPTH OF CLOSURE CONCEPT

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ABSTRACT

Using data from Duck NC (a wave-dominated, microtidal, sandy oceanic beach), depth of closure is critically evaluated. A meaningful closure is observed for most erosional events, and annual to 30 month time intervals, supporting the application of this concept within coastal engineering. However, the magnitude of depth of closure is sensitive to the definition and analysis approach utilized and estimates of closure need to be explicitly linked to this information.

The limit depth d_ℓ (Hallermeier, 1981) is found to define a conservative bound to the observations of closure during erosional events and in those annual cases where we have data. This confirms the ability to compute a meaningful limit depth simply using extreme wave conditions. At longer time scales there is evidence of a decoupling of the relationship between d_ℓ and observed depth of closure, the observations increase less rapidly than the predictions of d_ℓ. Understanding how closure evolves from individual erosional events to annual and longer time intervals improves the interpretation of sparse surveys and can assist engineering judgement when applying closure predictions.

INTRODUCTION

Depth of closure (DoC) is a widely-used concept within coastal engineering whieh describes the seaward limit of appreciable depth change (Hallermeier, 1978; 1981; Nicholls *et al.*, in review). It is based on the observation that repetitive beach-nearshore profiles show a decline in vertical variability with increasing depth. Empirically, a closure depth is observed in most high-quality profile data, corresponding to a pinch-out depth

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below which depth changes become small (Figure 1). DoC is often used to infer a seaward limit to significant cross-shore sediment transport, leading to applications such as: (1) estimating coastal sediment budgets (*e.g.*, Hands, 1983); (2) numerical modeling of coastal change (*e.g.*, Kraus and Harikai, 1983) and (3) beach nourishment design (*e.g.*, Stive *et al.*, 1991).

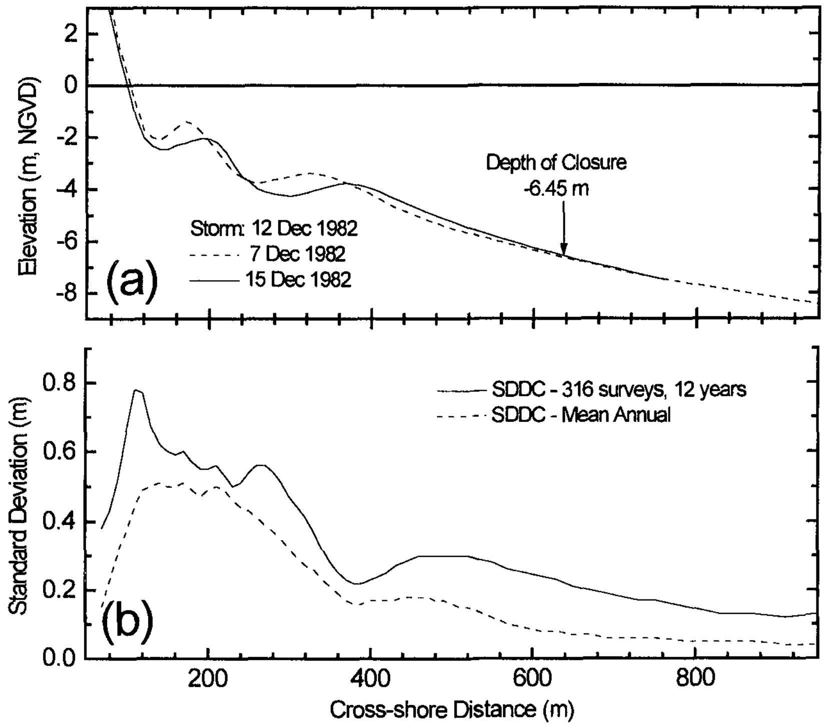

Figure 1. Example of (a) depth of closure produced by single storm, and (b) standard deviation of depth change (SDDC) over a typical year and 12 years. Variability decreases offshore, but increases with time scale. (Profile line 188, Duck, NC).

At sites with repetitive, beach-nearshore profile data, empirical estimates of DoC may be made directly. However, such sites are unusual and DoC is normally estimated using a range of possible indicators (USACE, 1984). The only analytical method to estimate DoC has been proposed by Hallermeier (1978; 1981). Annual DoC is the seaward limit of the littoral zone (depth — d_ℓ) which can be estimated using extreme wave conditions. In a generalized time-dependent form:

$$d_{\ell,t} = 2.28H_{e,t} - 68.5(H_{e,t}^2/gT_{e,t}^2) \qquad (1)$$

where $d_{\ell,t}$ is the predicted DoC over t years, referenced to Mean Low Water; $H_{e,t}$ is the non-breaking significant wave height that is exceeded 12 hours per t years, $(100/730t)\%$

of the time); $T_{e,t}$ is the associated wave period; and g is the acceleration due to gravity.

The detailed characteristics of DoC, including the validity of Equation 1, have been evaluated (Nicholls *et al.*, in review) using 12 years of profile data collected at the Field Research Facility (FRF) of the U.S. Army Engineer Waterways Experiment Station's, Coastal and Hydraulic Laboratory (formerly the Coastal Engineering Research Center), located in Duck, NC, U.S.A. This paper extends previous analyses, develops additional conclusions, and examines implications for coastal engineering design and practice.

THE DUCK DATA SET

Duck, NC is a wave-dominated, microtidal sandy beach located on the Atlantic Ocean (Birkemeier *et al.*, 1985). The beach-nearshore profile data used in this study were eollected to about 8-m depth along four profile lines (58, 62, 188, and 190). On these lines, offshore contours are relatively straight and one or two nearshore bars are usually present. These bars tend to be three-dimensional (Lippmann and Holman, 1990). Surveys are typically collected every two weeks and after most storms, providing pre- and post-storm profiles. Operational survey accuracy is <3 cm (Lee and Birkemeier, 1993).

Wave height and period data were collected every six hours, with hourly measurements during storms. Tidal elevation is also measured on site, with the mean tide range being about 1 m. Mean Low Water (MLW) is 0.42 m below National Geodetic Vertical Datum (NGVD). For more details on the data set see Lee and Birkemeier (1993), Larson and Kraus (1994), Lee *et al.* (1995; in review) and Nicholls *et al.* (in review). All observations of DoC are given relative to MLW as this appears to be an appropriate reference level for DoC estimates based simply on wave dimensions (Hallermeier, 1981; Nicholls *et al.*, in review).

DEFINITION AND INTERPRETATION OF CLOSURE

DoC is a fundamental morphodynamic boundary separating a landward active zone from a seaward less active zone *over the period defined by the profile observations used to define closure.* It is not an absolute cross-shore boundary and some depth change, and hence some cross-shore transport is expected to occur at DoC and further seaward (*cf.* Hallermeier, 1981). The position of DoC depends on several factors, including definition. Time scale is also significant as profile activity increases with time scale and a fixed closure criterion will typically move offshore as time scale increases (*e.g.*, Figure 1(b)). (Note that data accuracy often influences our ability to resolve DoC, but at Duck this is a minor issue). The processes which are observed to control DoC at Duck are the typical annual to decadal storm-accretion processes of the beach-nearshore zone (Lee *et al.*, in review), but at longer time scales, shoreface processes will probably control closure (*cf.* Stive and DeVriend, 1995). Therefore, while the concept of DoC is relatively simple, stating its magnitude at any site as x meters is meaningless without qualification eoncerning the definition utilized and the pertinent time scale. In some cases, closure may not be susceptible to a practical empirical definition, as observed by Inman *et al.* (1993) in samples of surveys at Oceanside, CA which include major storms in 1982/83.

DoC can be defined for (1) events, such as storms, (2) time-interval (or endpoint) change, which ignore intermediate changes (or in practical terms is equivalent to analysis of a typical sporadic survey program), or (3) time-integrated (or cumulative) change. While events can be related to specific energetic wave conditions and processes (*e.g.*, erosion), time-interval and time-integrated changes are controlled by the balance of erosional processes (rapid offshore transport during high energy wave events) and accretional processes (slow, but continuous onshore transport between erosional events) (Lee *et al.*, in review).

To illustrate and examine the variability of DoC due to different definitions at a site with frequent surveys, annual DoC values from profile lines 62 and 188 at Duck are presented in Table 1. Annual time-interval DoC using three fixed depth change criteria: (6 cm, 10 cm and 15 cm) are considered; In this analysis, profiles are compared proceeding seaward to determine where the profile change consistently declines below the depth change criterion, hence defining closure. Annual time-integrated DoC is measured using the standard deviation of depth change (SDDC) which avoids bias from outliers —

Table 1. Annual closure (m, MLW) derived from three fixed change criteria and from an SDDC analysis, including the annual elevation range shown at closure. Each annual period is July to July (fixed criterion) and July to end June (SDDC). "*" indicates non-closing case.

Start Year	Profile Line 62					Profile Line 188				
	Fixed Depth -Change Criteria			SDDC		Fixed Depth -Change Criteria			SDDC	
	6 - cm	10- cm	15- cm	Depth (m)	Range (m)	6- cm	10- cm	15- cm	Depth (m)	Range (m)
1981	7.2	6.5	4.4	5.4	0.16	7.9	7.6	7.4	5.8	0.16
1982	8.0	6.1	5.9	6.7	0.12	6.4	6.2	6.0	6.6	0.19
1983	6.4	6.2	6.0	6.2	0.14	7.7	5.9	5.7	6.0	0.13
1984	6.3	5.0	3.8	6.6	0.12	7.3	6.6	6.2	5.1	0.21
1985	8.0	7.5	6.8	5.1	0.20	*	8.3	6.6	4.8	0.20
1986	*	*	8.0	6.9	0.23	*	*	7.7	8.3	0.18
1987	6.3	6.1	5.9	6.1	0.13	6.0	5.8	5.6	6.0	0.12
1988	*	*	*	*	*	*	*	*	7.7	0.43
1989	*	*	*	7.3	0.13	*	*	5.1	7.2	0.20
1990	*	*	5.2	5.7	0.16	*	*	*	6.8	0.24
1991	*	8.1	5.3	5.9	0.22	7.9	7.4	4.8	5.6	0.22
1992	6.9	6.3	6.0	6.8	0.16	5.2	5.0	4.1	6.0	0.14

the DoC then corresponds to the start of a non-zero tail (Kraus and Harikai, 1983). Note that dcpth change at DoC is a variable defined by the standard deviation envelope and hence there is more potential for an irregular criterion using this approach. Annual SDDC-defined closures from Profile line 62 are illustrated in Figure 2.

The first observation concerning Table 1 is that annual DoC is not always defined within the surveys (≤8-m depth): the 6-cm fixed criterion defines 58% of closures, while SDDC defines 96% of closures. The largest annual DoC is usually given by the 6-cm change criterion: the 10-cm and 15-cm changes are on average about 90% and 80% of the

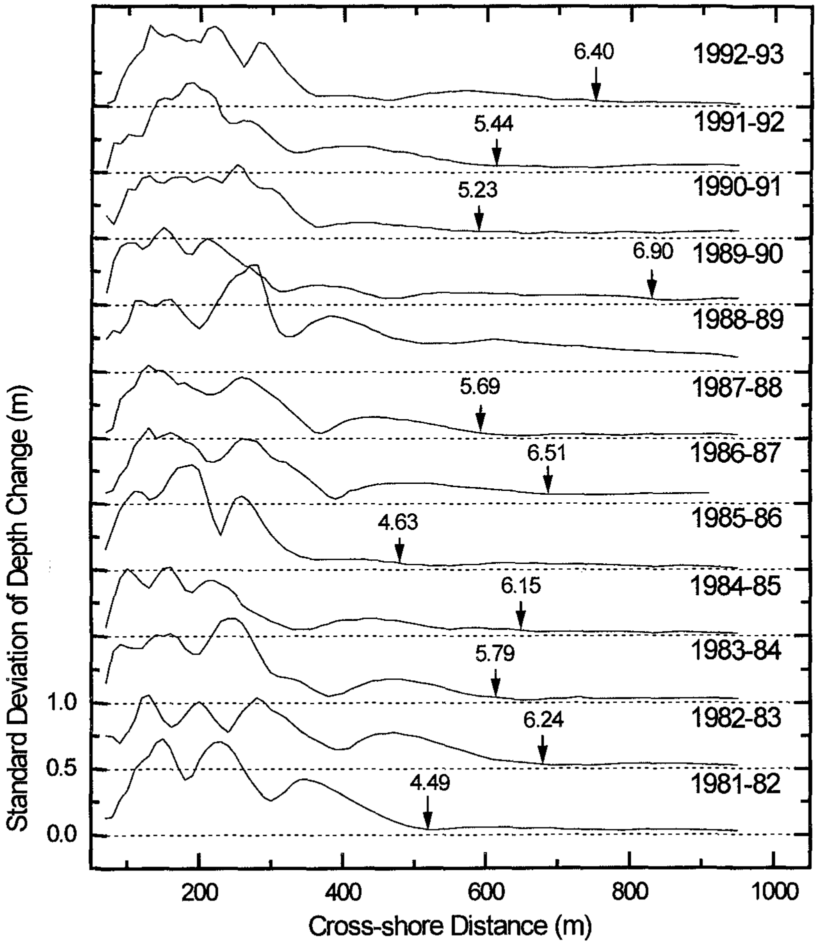

Figure 2. Standard deviation of depth change envelopes for 12 annual periods from July 1981 until end June 1993 (Profile line 62). Arrows mark SDDC-derived closure and are labeled with depths in m below MLW.

6-cm changes, respectively. Clearly, DoC defined with any constant depth change criterion is just one of a family of possible DoCs, depending on the depth change criterion selected. The smaller the depth change criterion, the greater the proportion of the active profile which will be defined.

The SDDC-defined boundary defines most annual DoCs, including periods of significant profile accretion when all the fixed change criteria fail. However, these cases are associated with a larger non-zero tail, indicating larger uniform changes to the seaward limit of the profile envelope than in typical years. On average, the SDDC DoC lies between the 10-cm and 15-cm time-interval DoC, but this relationship is not apparent for the non-closing cases using a fixed change criterion. Therefore, it is concluded that while the SDDC approach is a reasonable empirical method to define DoC, at Duck it shows bias towards smaller annual closure when there are uniform profile changes at the seaward ends of profiles. A fixed, standard deviation criterion (*e.g.*, 10 cm) would provide results more consistent with the fixed change criterion.

It is also noted that these annual SDDC analyses differ from Larson and Kraus (1994). Using all the Duck data from 1981 to 1991, they discriminated a boundary at about 3.6 m below MLW (400 m offshore). However, comparing Figures 1 (b) and 2 shows that while the minimum at 400 m is an intriguing aspect of the survey data, it is part of a larger declining trend to greater depths. Therefore, this position should not be eonsidered the start of a non-zero tail in the sense of the results in Table 1.

Clearly, different definitions for DoC yield different depth estimates, so any stated empirical result needs to make the definitions explicit. Closure at Duck due to erosional events and over annual and longer time scales is now examined in more detail.

DEPTH OF CLOSURE DURING EROSIONAL EVENTS

Predictions Using Hallermeier (1981)

DoC during erosional events, defined by consistent offshore bar migration, was measured for 68 events with high waves (>2 m height) (Nicholls *et al.*, in review) and is henceforth referred to as erosional event-dependent (E-D) DoC. Following the rationale behind Equation 1, which defines a depth where most waves will not have experienced shallow water breaking, analysis of DoC during erosion at Duck shows that a 6-cm change criterion is the best indicator of closure. It is also most consistent with the documented survey accuracy. A 6-cm change criterion is used in all subsequent analysis

Equation 1 is found to define a conservative bound to the observations (Figure 3), agreeing with Hallermeier's (1981) original recommendations concerning input parameters. Below this limit, the observations show considerable scatter which is partly explained by the pre-event bar configuration — the largest DoC appear to be associated with the most dissipative profile morphology, namely, single outer bars (bar erest about 300 m offshore). Three erosional events produced observed DoCs which were near the survey limit (8-m depth), while three erosional events did not close within the measured profile. These results do not contradict Equation 1 as d_ℓ>8 m for those cases which close beyond the survey range.

Using an empirical best-fit approach to the data in Figure 3, a typical erosional event realizes 69% of the change predicted by Equation 1 (>95% confidence) (Figure 3):

$$d_E = 0.69 \ d_\ell \qquad (2)$$

where d_E = observed E-D DoC. However, Equation 2 is affected by the fact of missing observations and its validity for other sites is uncertain.

Probability Analysis

The 68 available observations of erosional E-D DoC approximately conform to a lognormal probability distribution, *i.e.* plot near a straight line in Figure 4. The observations have been ranked in ascending order from i = 1 to 68, then assigned evenly-spaced probabilities of (i-0.5)/N, where N = (68+3); this procedure allows for the three presumably higher missing observations noted in the previous section. A lognormal probability distribution arises "when many random quantities cooperate multiplicatively so that the effect of a random change is in every case proportional to the previous value of the quantity" (Sachs, 1984, p. 107). For these nearshore DoC, the controlling variables include wave height and period and pre-event profile geometry (Nicholls *et al.*, in review).

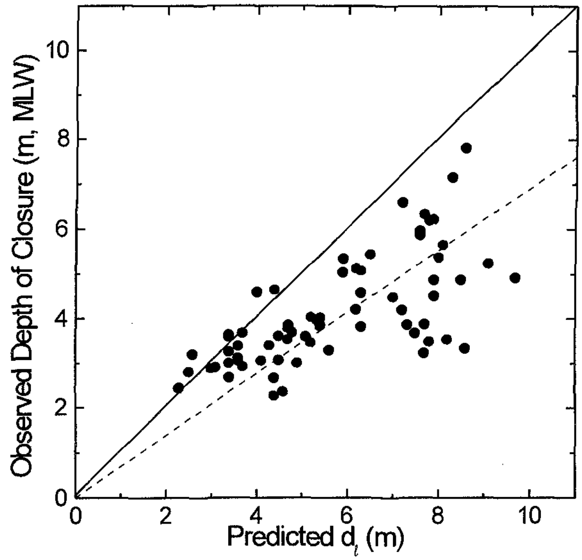

Figure 3. Observed versus predicted depth of closure (averaged alongshore) during 68 storms The best-fit line (Equation 2) is dashed.

Such well-behaved observations suggest a coherent sample of erosional events at Duck, so that extrapolation to rarer events than those yet recorded at the site maybe meaningful. One approach to extrapolation is to use annual maxima of the erosional E-D DoC, giving observations a direct basis in annual probabilities. Figure 4 also displays the nine observed annual maxima (three missing) in the same basic format, with these values showing fair conformance to a shifted lognormal probability distribution. The median annual extreme eorresponds to 50% annual probability, or a recurrence interval of 2 years. Note that a lognormal distribution yields lower extremes than a exponential distribution, which would typically describe wave heights (USACE, 1984).

Empirical evidence in Figure 4 consistently supports the order-of-magnitude

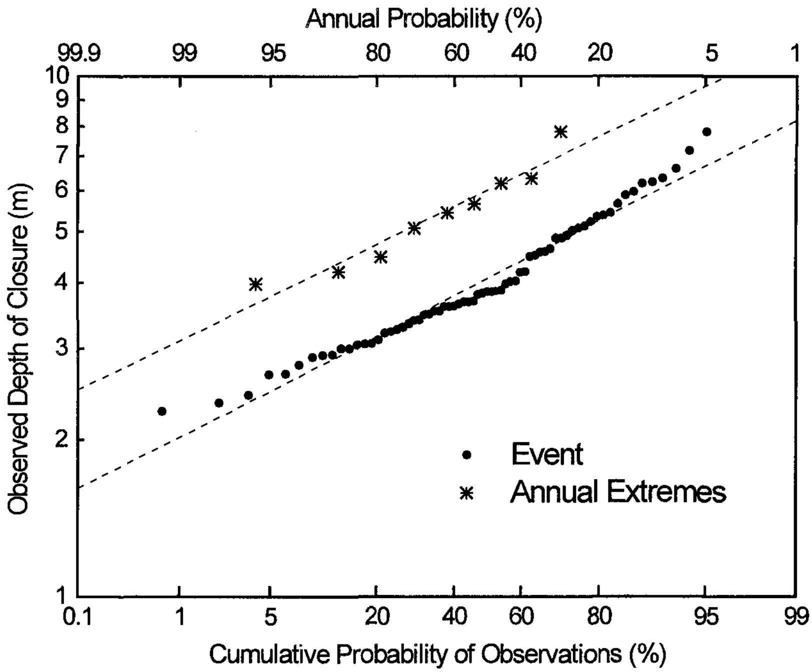

Figure 4. Lognormal distributions of all observed erosional event-dependent cases, comprising all observations (Event), and the nine observed annual extremes

estimates for extreme DoC in Table 2. These projections suggest that during more extreme erosional events, advances of DoC into water depths beyond 8- to 9-m depth below MLW are rather rare. This behavior is broadly consistent with (1) the predictions of Equation 1 which suggest that over 12.5 years, DoC during erosional events only exceeded 9-m on four occasions (or 6% of cases), and (2) conclusions about observed DoC in a probabilistic context, derived from an independent analysis of all the Duck survey data from 1981 to 1991 (Larson and Kraus, 1994).

Table 2. Approximate recurrence interval for the annual maximum erosional event-dependent closures based on a probability analysis (see text for more details).

Closure Depth (m below MLW)	7	8	9	10	11
Approximate Recurrence Interval (years)	2.5	5	12	30	70
Annual Probability (%)	40	20	8	3	1.4

DEPTH OF CLOSURE OVER ANNUAL AND LONGER TIME INTERVALS

This section examines the magnitude of DoC over a range of time intervals (1, 1.5, 2, 2.5, 4 and 8 years), including the applicability of Equation 1. DoC was evaluated using a time-interval approach (*i.e.*, comparing surveys separated by a fixed time interval, as defined earlier) with a 6-cm change criterion. Surveys three months apart in time over the period July 1981 to October 1993 were selected as the basic data set for analysis. This gave 46 time periods for annual closures, 44 annual time periods for 18-month closure, etc.

Predictions Using Hallermeier (1981)

An important result is that time-interval (T-I) DoC is generally deeper than the largest E-D DoC during the same time period. For the annual case, the residuals (d_ℓ - observed DoC) are about 1 m smaller than the erosional events, as shown in Figure 5. This demonstrates that T-I DoC is an integrated response to both erosional and accretional processes, rather than simply indicating the biggest erosional event during a period. Equation 1 is known to fail under accretional conditions, producing estimates that are generally smaller than the observed DoC (Nicholls *et al.*, in review). Therefore, if erosional processes dominate a period, Equation 1 may have more predictive capability than if accretion dominates the period.

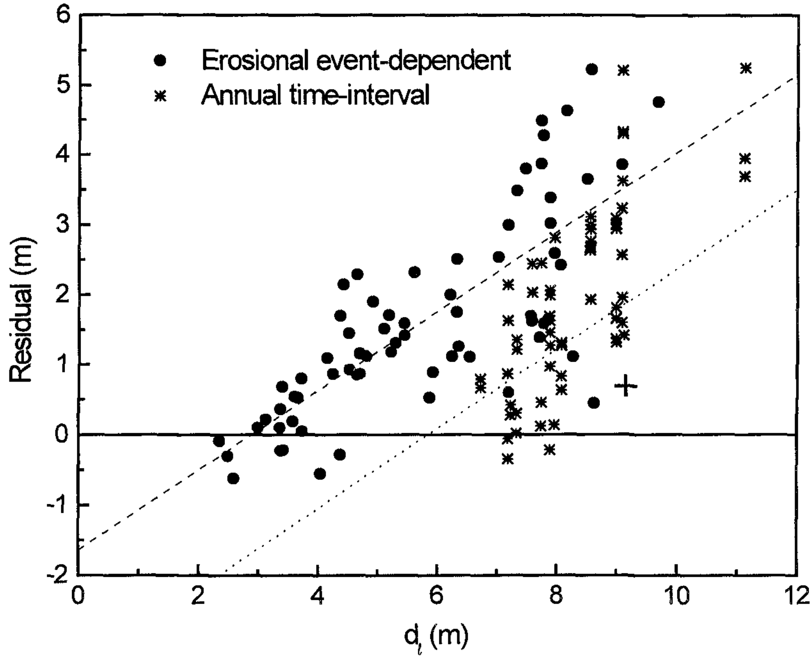

Figure 5. Residuals (d_ℓ - observed DoC) versus d_ℓ for erosional event-dependent closures and annual time-interval closure using a 6-cm change criterion. The dashed line is the best-fit to the erosional data, while the dotted line is the same line offset to pass through the approximate median of the annual time-interval data.

As the time interval between surveys increases, fewer cases close within the surveyed profile range at Duck ($\leq$ 8-m depth below MLW) — 65% of annual interval cases, 63% of 18-month interval cases, 61% of 2-year interval cases, 51% of 30-month interval cases, 44% of 4-year interval cases and only 3% of 8-year interval cases close. The 8-year intervals always include significant profile movement and hence 6-cm closure is lost, except in one case. In all the non-closing cases, net profile change (>6 cm) is occurring seaward of 8-m depth.

Equation 1 is found to provide a useful conservative bound to those annual DoC which are defined within the survey range, see Figure 6. Using an empirical best-fit approach to the data, over a typical year, 76% of the change predicted by Equation 1 occurs (>95% confidence):

$$d_{T,1} = 0.76\ d_{\ell,1} \qquad (3)$$

where $d_{T,1}$ = observed annual T-I DoC. Note that Equation 3 has a numerical coefficient 10% larger than Equation 2.

Most of the annual cases which do not close are consistent with Equation 1 as $d_{\ell,t}$>8 m. However, there are five cases (8%) which are predicted to close but did not within the survey extent. This characteristic is also observed in the 18 month, 2 year and 30 month interval data, comprising 9%, 8% and 17% of cases, respectively. All the time periods where this behavior is observed were characterized by slow near-continuous onshore feed of sand from the upper shoreface (>5-m depth) (*cf.* Lee *et al.*, in review). Under these conditions, Equation 1 might be expected to be inapplicable, as already discussed. The large number of missing observations and the scatter in results makes objective assessment of the predictive value of Equation 1 more difficult to assess than for the erosional events.

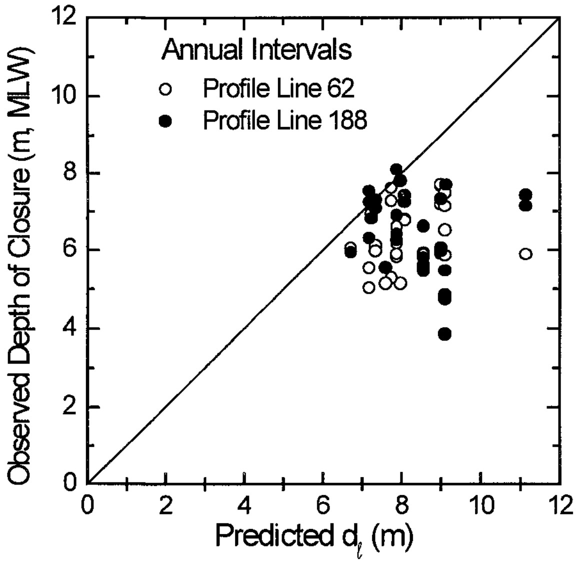

Figure 6. Observed versus predicted annual depth of closure for individual profiles. The dashed line is the best-fit (Equation 3). Of the 32 cases which are not observed to close, $d_{\ell,1}$> 8 m for 27 cases.

Sensitivity Analysis

The data were examined considering median values to circumvent the missing values, and annual up to 30 month time intervals. (Longer intervals have too few observations to define medians). The cases with d_ℓ of 11.1 m due to the most energetic wave event of record occurring on 31 October 1991, the "Halloween storm," are disearded as outliers not likely to be observed. The remaining data is divided as near equally as possible into a low and high bin, while retaining the capacity to define observational medians: *i.e.*, a meaningful central tendency for measurements. The median for each bin was then determined, treating all missing values as higher than available observations. The sensitivity of observations to predictions is simply the ratio of the difference in observation medians between the two bins, to the difference between the prediction medians. The sensitivity results are presented in Figure 7. Annual observations appear more strongly related to predictions than the erosional event observations. Above the annual time scale, there is a significant decline in sensitivity to negligible levels at 24- and 30-month time intervals. This indicates that at time intervals longer than one year, the observed closures are increasing much less rapidly than Equation 1 would suggest — *i.e.* the observations and predictions are decoupling. (Of course, Equation 1 still provides estimates of closure that tend to be larger than the observations, so that its predictions have value as a conservative bound.) From this evidence, Equation 1 is interpreted at Duck as being meaningful up to annual time seales, as originally proposed by Hallermeier (1978; 1981).

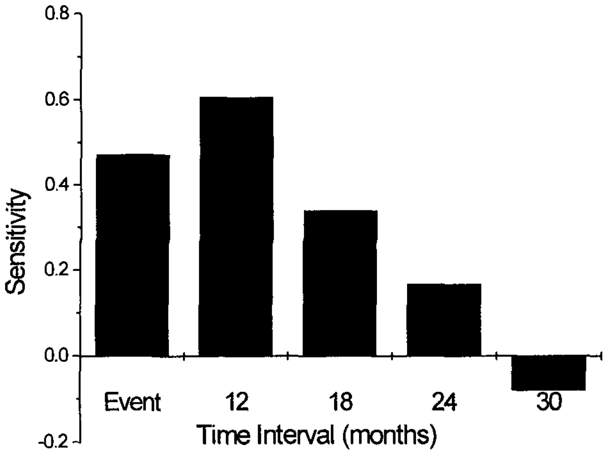

Figure 7. Sensitivity of observation to $d_{\ell,t}$ as a function of time interval: from individual events to a 30-month interval.

DISCUSSION

The time-interval behavior of closures in this extensive database appears to validate a common empirieal definition of a useful DoC: such analyses usually group all available surveys of a profile, regardless of the time interval between data (*e.g.*, Inman *et al.*, 1993). The results documented here indicate that a closure estimate from such analysis is meaningful for a site, provided that the time interval of available data includes at least one seasonal profile translation. However, Figure 2 shows that profile variation in any one year may be a poor description of the statistical properties of a profile and more than one annual cycle of profile data is preferred. Further, a practical DoC may not be evident if the time span included exceptionally energetic wave sequences yielding a permanent profile translation (Inman *et al.*, 1993).

Some previous analyses may appear to be a little misleading about the DoC implications of the Duck profile database. Our analyses focusing on isolated energetic episodes have revealed many cases of resolvable and volumetrically significant changes at water depths well beyond the 4-m or 6-m deduced as limits by Larson and Kraus (1994). In addition, our analysis, focusing on intervals of one year clearly established that, within survey limits, an annual DoC is the prevalent situation at Duck, despite an absence of definite DoC over some longer time spans (Inman *et al.*, 1993). For each type of observation, the seaward limits of profile change are related to extreme wave conditions by Equation 1. Previously repeated conclusions about DoC at Duck are empirically supported by particular analyses addressing certain longer time intervals, but the present findings reflect more detailed and intensive examination of the same database. Additions to and analysis of that database continue at present, and a more coherent picture is expected to emerge progressively.

As Equation 1 provides a robust conservative bound for significant cross-shore sediment transport at Duck for individual erosional events up to the annual time scale, simply knowing the extreme wave conditions will allow estimates of closure to be made at similar microtidal, wave-dominated sites. Interestingly, both Equation 3 and the sensitivity analysis indicate a stronger relationship between annual DoC and Equation 1 than erosional DoC and Equation 1. Given that Equation 1 is an event-based formulation (*i.e.*, based on the biggest event in a period), this is a surprising result. Above an annual time scale, the available evidence suggests that DoC increases less rapidly than Equation 1 would predict. This is an important result which disagrees with earlier work (*e.g.*, Stive *et al.*, 1992) and has important implications for application. While we are unsure about applying Equation 1 to a t-year time interval, we are more confident about applying Equation 1 as a conservative bound with known wave conditions during an t-year erosional event. An estimate of how far sand might be carried offshore during extreme events can assist in analysis of a range of problems. In intervening periods between erosional events when Equation 1 may not be applicable, sand is generally being slowly transported onshore at open-coast sites such as Duck (Lee *et al.*, in review) with beneficial effects for the beach-nearshore sediment budget. In more sheltered sites with more limited swell, this may not be the case.

A key question is the specification of the wave information to use in Equation 1. The predictions presented here are based on 12-hour exceeded wave height and period measurements at a waverider buoy, 6-km offshore at a depth of about 18-m. Therefore, the measurements are shallow water, but well seaward of the breaker zone. In many cases such data are unavailable, although other wave measurements or hindcast wave information may be available. Improved guidance on optimum wave inputs to Equation 1 need to be developed.

Another problem is the variation in $d_{\ell,1}$ at any site due to variations in annual extreme waves. Twelve years of wave data at Duck show that $d_{\ell,1}$ can vary by more than 2 meters depending on the annual period selected: the 25th percentile is 7.7 m, the median is 8.7 m and the 75th percentile is 9.2 m below MLW. Given the apparent tendency for overprediction of closure depth, most attention might be focused on the two lower values. Taking beach nourishment as an example, selecting a smaller DoC will result in a lower initial project cost, but it may be prudent to plan for more frequent renourishment. This type of analysis will help to identify the trade-offs when selecting from the range of legitimate DoC estimates.

Despite the apparent decoupling of Equation 1 and observations with increasing time scale, it is apparent that application of DoC requires a more explicit consideration of time scale. At Duck, longer time scales are associated with greater profile variability at depth (*cf.* Figure 1(b)), implying larger DoC for a constant depth change criterion. The surveys define DoC for 95% of erosion episodes and for 65% of annual intervals, but over the 12-year window they have failed to define a seaward limit of the profile envelope. An important lesson is that when designing long-term, high accuracy, beach monitoring programs to define the profile envelope, the distribution of $d_{\ell,1}$ helps to define a realistic *minimum* target depth for routine surveys. At Duck, the surveys considered in this paper typically only reach the 25th percentile of $d_{\ell,1}$, with the maximum depths attained being less than the median $d_{\ell,1}$. With our present knowledge of Duck, occasional surveys to the 75 percentile of $d_{\ell,1}$ would appear a reasonable target depth for Duck and similar sites.

CONCLUSIONS

A meaningful depth of closure is observed at Duck under erosional events and a range of time intervals from 1 year to 30 months. The depth limit $d_{\ell,t}$ is found to be robust and useful for erosional events and annual time intervals. Therefore, with limited environmental information (the event or annual 12-hour exceeded wave height and period), a reliable closure estimate apparently can be made. However, Equation 1 is a conservative bound to the observed closures and results should be applied with this in mind. At longer time scales, the observations and Equation 1 decouple as observed closure appears to increase more slowly than the predictions of $d_{\ell,t}$ would suggest.

Knowing the nature of Equation 1 and how closure evolves with increasing time scale, coastal engineers can make better judgements when interpreting sparse survey data. They can also optimize application of a closure value by considering the trade-offs in selecting from a range of legitimate estimates for a site. Finally, the Duck data indicates our limited understanding of cross-shore sand exchange between the beach and the upper shoreface. To capture more of the change for extreme cases, routine measurements are required to greater depths. Collection and investigation of the Duck data set continues.

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