

DEPTH OF CLOSURE: IMPROVING UNDERSTANDING AND PREDICTION

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ABSTRACT

The closure concept is a fundamental cross-shore boundary condition for morphodynamics and other applications such as beach nourishment and sediment budgets. This paper examines closure at a range of scales, particularly from events up to years. At these scales, closure is primarily a function of direct external forcing (cross-shore redistribution of sediment by waves), indirect external forcing (sediment loss/gain by littoral transport and the resulting profile translation) and internal system dynamics (bar dynamics). Therefore, simple wave-based models such as Hallermeier (1981) cannot be expected to predict the actual closure, although they can predict distributional properties such as the limit. A general approach to develop more user-orientated estimates of closure over a range of timescales is outlined based on equilibrium theory. This will include a user-defined depth change criterion as a function of timescale.

INTRODUCTION

Depth of closure is widely used within coastal engineering as an empirical measure of the seaward limit of *significant* cross-shore sediment transport on sandy beaches. More fundamentally, it is an important parameter which distinguishes two cross-shore zones with different levels of morphodynamic activity. The closure

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concept initially arose from the comparison of repetitive beach-nearshore profiles (henceforth beach profiles). Such profiles define an envelope of variation which declines with depth. The seaward limit of this envelope is generally interpreted as the "depth of closure". However, the precise location of closure is a matter of the depth change criterion used to define closure from a set of measurements: the larger the criterion the more deeper changes are ignored and the shallower the estimate of closure. In practical terms closure is often defined using the measurement accuracy.

Models to predict closure are limited. Using an argument based on the critical value of a sediment entrainment parameter, Hallermeier (1981) developed the only analytical approach to estimate an annual depth of closure on sandy beaches (d_{ℓ}). It is a function of extreme wave conditions and in a generalised time-dependent form is:

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

where $d_{\ell,t}$ is the predicted depth of closure 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; $T_{e,t}$ is the associated wave period; and g is the acceleration due to gravity. This method explicitly recognises that some sediment movement will occur seaward of d_{ℓ} .

Given that depth of closure is an important morphodynamic parameter common to all scales, it has been explored as part of the EU-funded MAST III PACE (Predicting Aggregated-Scale Coastal Evolution) project. This has included investigating its field characteristics, testing existing models and developing new models, which cover the range of engineering timescales (≤ 50 years) (e.g., Nicholls et al., 1996; Capobianco et al., 1997). The datasets which have been examined are summarised in Table 1. It is important to distinguish the wide range of time (and space) scales considered in Table 1 and the following terminology is used: (1) small scale for events to seasons, (2) medium scale for one year to one decade, (3) large scale for decades to one century, and (4) very large scale for centuries to millennia (cf. Stive et al., 1990; Hinton and Nicholls, 1998). Collectively, these data covers the morphological response to individual storm events (small scale) up to the integrated effects of several decades of morphological evolution (large scale). All sites are wave-dominated, microtidal beaches, with the exception of Terschelling which is mesotidal.

The following generic results are apparent.

- Depth of closure is time and space-scale dependent, and generally increases with timescale (Capobianco et al., 1997).
- Depth of closure is a morphodynamic boundary, not a sediment transport boundary. Sediment transport should be expected to occur seaward of closure, especially during storms (Wright et al., 1991; Garcia et al., 1998). However, at the timescale defined by a closure measurement, the start of measurable morphological change is a good empirical indicator of an increasing capacity

for cross-shore sediment transport. At longer timescales, this may not be the case.

- At small scales, depth of closure is usually the product of bar migration due to surf zone processes (Nicholls and Birkemeier, 1997; Nicholls et al., 1998). As the scale increases, so beach-nearshore profile translation and ultimately shoreface processes come to control the location of closure (Hinton and Nicholls, 1998). At large scales on the Holland coast, it is possible to distinguish a “shoreward” closure due to breaking waves, reopening of the profile lower on the shoreface, and then a deeper middle/lower shoreface closure due to shoreface processes. Thus, the closure concept can define four distinct cross-shore zones at this scale.
- Equation 1 provides robust estimates of the *limit* to closure for individual erosional events up to the annual timescale (Nicholls et al., 1996; 1998; Garcia et al., 1998; Rozyński et al, 1998). At medium scales, it continues to act as a limit, but with an increasing tendency for overprediction. Equation 1 only considers cross-shore redistribution of sediment and excludes the effects of beach-nearshore profile translation (Nicholls and Birkemeier, 1997). In particular, it is invalid in areas which are accreting rapidly due to longshore supply of sand.
- Analysis of closure at a nourished site (Terschelling) finds that Equation 1 and pre-nourishment profiles provide a good estimate of the *limit* of post-fill closure (Marsh et al., 1998).

Therefore, the processes which control closure vary with scale. At small scales, closure is a product of episodic, short intense erosional events (and offshore transport), and/or more continuous accretional processes (and onshore transport) (Nicholls et al., 1998). Over days and weeks, we might associate closure with a specific process and cross-shore transport direction, but over seasons and longer, closure is the integrated result of onshore and offshore sediment transport. As the scale increases, so the number of processes which influence closure increases. At large scales, slow progressive morphological changes on the shoreface may become significant, moving closure to significantly greater depths than typically considered by engineers (Hinton and Nicholls, 1998). At very large scales, both models and geological evidence suggest that closure will lie at the base of the shoreface (cf. Stive and deVriend, 1995; Niedoroda et al., 1995; Cowell et al., 1995).

Based on these results, this paper reviews and refines our understanding of the methods available to predict closure for engineering application. Small and medium scales are considered using the Duck dataset (e.g., Lee and Birkemeier, 1993) for validation. Given that closure is user-defined, the concept can be generalised as a family of depth change contours, which define a number of cross-shore zones (Capobianco et al., 1997). This approach allows a user to select the most appropriate depth change criteria for their application.

Table 1. Summary of the datasets examined for depth of closure within the PACE project (see also Hamm, 1997)

Site	Period (yrs)	No of Profile Lines	Area Covered		Accuracy (cm)	Spring tidal range (m)	Typical extreme wave height (m)	Sources
			Long-shore (km)	Depth (m)				
Duck, USA	13	4	1	8	3	1.2	4 to 5	Nicholls et al. (1996; 1998), Nicholls and Birkemeier (1997), Capobianco et al. (1997)
Terschelling, the Netherlands	30	13	12	10	25	2.8	5 to 6	Marsh et al. (1998)
Holland Coast, the Netherlands	25	82	81	≤16	25	1.4 to 1.7	5	Hinton and Nicholls (1998)
Ebro Delta, Spain	4	36	40	15	10	<0.5		Garcia et al. (1998)
Lubiatowo, Poland	10	4	0.4	8	25	<0.5	2 to 2.5	Rozyński et al. (1998)

CONTROLS ON CLOSURE AT SMALL AND MEDIUM SCALES

When considering the prediction of closure, it is important to understand what forcings and internal dynamics influence this morphological response. Based on our present understanding, a conceptual model linking forcing to closure is shown in Figure 1. The primary forcing which produces closure under microtidal, wave-dominated situations appears to be wave action (Capobianco et al., 1997; Nicholls et al., 1998). The skill of Equation 1 in predicting the limit of closure for erosional events and annual timescales is one indicator of the importance of this forcing. Wave action may produce closure in two distinct ways: (1) *directly* by cross-shore redistribution of sediment; and (2) *indirectly* by net gains or losses of sediment due to longshore transport and the resulting profile translation (see Nicholls and Birkemeier, 1997). While the indirect effect of waves might be observed at small scales, it is more important at medium scales due to the cumulative effects of littoral transport.

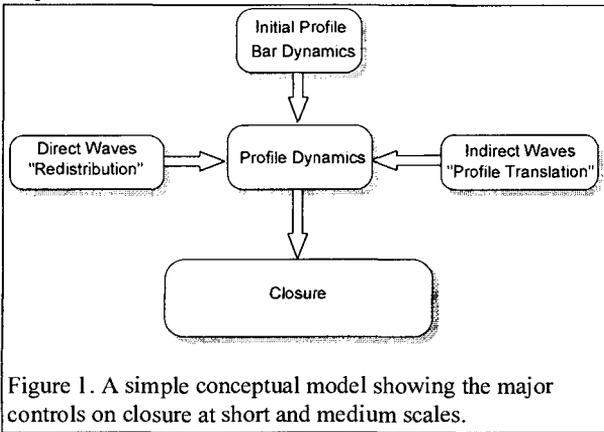


Figure 1. A simple conceptual model showing the major controls on closure at short and medium scales.

The response to this forcing is constrained by the internal dynamics of the morphological system. At small scales, the pre-event bar configuration influences closure during erosional events (Nicholls and Birkemeier, 1997; Nicholls et al., 1998). At medium/large scales, the shoreward closure along the

Holland coast shows two distinct closure provinces in response to (broadly) the same wave climate (Hinton and Nicholls, 1998). However, these two provinces can be directly related to zones of distinct bar behaviour, showing that bar morphodynamics influence closure at these scales.

Therefore, closure is a response to the direct and indirect wave forcing, conditioned by the starting morphology and/or bar dynamics. In terms of prediction this has important implications. To predict closure both the forcings and the internal dynamics need to be described and this is not presently possible (see Capobianco et al., 1997). Models which only consider the forcing can only predict properties of the distribution of closure for that forcing (i.e., a minimum, or a maximum, or a mean). This limits our prediction capability, although just knowing the limit to closure is often useful to engineers (Nicholls et al., 1996; 1998).

CLOSURE AT SMALL SCALES

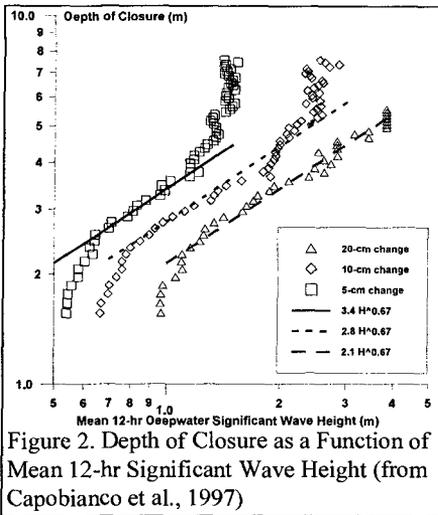
Nicholls et al. (1998) examined closure (defined with a 6-cm depth change criterion) at weekly to monthly intervals using data from Duck. Each closure event was defined as erosional if associated with consistent offshore bar movement, and accretional if associated with consistent onshore bar movement. The *limit* to closure is well-predicted by Equation 1 during erosional events (the closure response can normally be related to a specific storm). However, the scatter below Equation 1 is large and partly due to pre-event profile configuration: for the same wave forcing deeper closures occur when an outer bar is well-developed (Nicholls and Birkemeier, 1997). An empirical best fit shows that observations are 67% of predictions. Under accretional conditions, Equation 1 often underpredicted the observed closure. This is not a surprising result as Equation 1 is based on extreme waves, while accretion is a slow steady process which may have occurred near continuously between surveys.

To generalise closure at small scales for a range of depth changes, Capobianco et al. (1997) examined empirical relationships with the wave forcing, again using data from Duck. Closure was defined using an automatic algorithm for 5-cm, 10-cm and 20-cm depth change criteria. Empirical distribution functions were derived from the waves and the calculated depths. Assuming that there is a general relationship between waves and depth variation, the exceedance probabilities can be matched (i.e., the $x\%$ highest waves produce the $x\%$ largest depth changes). Note that accretional and erosional closures are not distinguished. The result is given in Figure 2.

An empirical fit which allows extrapolation to larger wave heights is also shown:

$$D_p = k.H^{0.67} \quad (2)$$

where D_p is the predicted depth of closure, H is the *mean* wave height over the 12 hour exceedance (see Equation 1), and k is a constant of 2.1, 2.8 and 3.4 for 20-cm, 10-cm and 5-cm change, respectively. For the deeper closures, Equation 2 provides a good fit for 20-cm change. However, for the 5-cm and 10-cm change, there is significant underprediction for the deepest closures that one would most like to predict. However, this could represent spurious data generated by the automatic algorithm used to estimate closure and an independent check of these results is required.



The dataset of accretional and erosional cases from Duck developed by Nicholls et al. (1998) is suitable for such a check as it has been manually quality controlled to remove spurious values. It is compared with Equations 1 and 2 in Figure 3. The general form of Equation 2 is shown to provide a reasonable limit to the all the closure observations. For 5-cm change, the accretional and erosional cases occupy distinct areas, as discussed above. Equation 2 provides a limit to both the accretional and erosional cases, but Equation 1 provides a better limit for the deeper erosional cases. For 20-cm change, there is less distinction between the erosional and accretional

cases, and Equation 2 still defines a reasonable upper limit to the entire dataset, although this can be improved with adjustment to k (Table 2). For the deep erosional cases, Equation 1 still provides a better limit than Equation 2 if an empirical adjustment is made (Table 2).

Table 2. Empirical coefficients to determine the limit to closure using Equations 1 and 2 based on the data in Figure 3.

Depth Change Criteria (cm)	Equation 1 Adjustment (for erosional cases only)	adjusted k for Equation 2 (all cases)
5/6	100%	3.4
10	90%	3.2
20	75%	2.4

The general applicability of Equation 2 to sites other than Duck is less certain, given its empirical basis. However, it provides useful guidance and shows the potential for the prediction of a limit to closure for a range of depth change criteria. Finally, these results reinforce the value of distinguishing erosional from accretional closures at small scales.

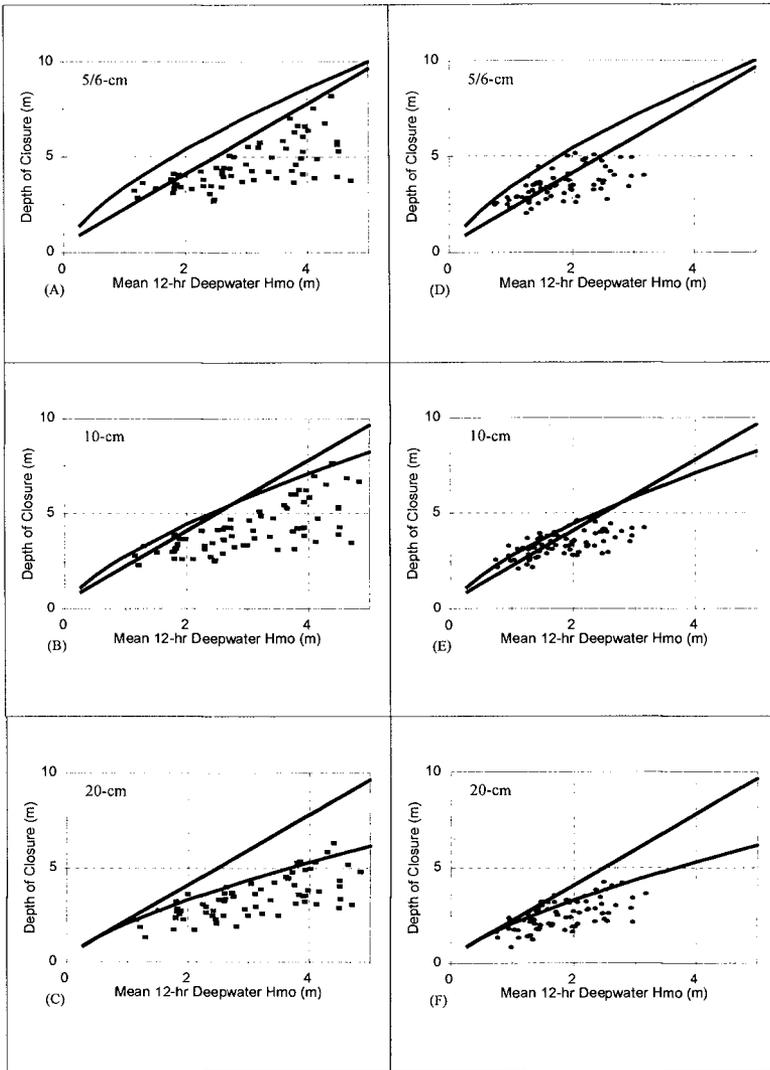


Figure 3. Depth of closure versus the mean extreme 12-hour deep-water wave height. Equation 1 (straight line) and Equation 2 (curved line) are shown together with data from Duck using a 5/6-cm, 10-cm and 20-cm depth change criteria. (A), (B) and (C) show erosional cases, and (D), (E) and (F) show accretional cases.

CLOSURE AT MEDIUM SCALES

Closure at medium scales is an integrated response to both erosional and accretional processes, including cross-shore redistribution of sediment and profile translation. At the annual timescale, Nicholls and Birkemeier (1997) showed that while Equation 1 acted as a limit to the closure data, volume change was an additional controlling factor. Profile retreat and volume loss reduces closure compared to a case with no translation, while it was inferred that volume gain and profile advance enhanced closure compared with no translation. The residual ($d_{\theta,t}$ - observed closure) versus volume change is shown for annual, two-yearly and four-yearly time intervals in Figure 4. Linear regression explains 21% of the variance. However, net volumetric changes at Duck have been relatively minor over the period of observations. An analysis of more data on closure from other sites with large net volume changes is needed to better understand this factor.

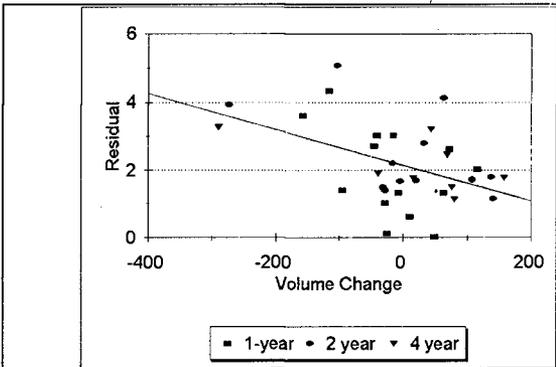


Figure 4. Residual (m) versus net volume change (m^3/m) at Duck for 1-year, 2-year and 4-year intervals and a 6-cm depth change criterion.

However, these results show that a better test of Equation 1 is under conditions of no volume change. In the subsequent analysis, only closures defined using a 6-cm criterion using profiles where the volume change is $<50 m^3/m$ are considered. Table 3 summarises the data in terms of residuals, including erosional events for comparative purposes. While the sample size is small, the mean residual is smallest

for the annual timescale, and then increases with timescale. Regression coefficients (forced through the origin) are also given in Table 3:

$$D_c = a d_{\theta,t} \quad (3)$$

where D_c is the observed closure and a is the regression coefficient. The regression coefficient shows a similar pattern to the mean residuals and is closest to unity at the annual timescale. These results are all consistent with the results of Nicholls et al. (1996) that Equation 1 provides best agreement with observations at annual timescales.

Table 3. Mean residuals and regression coefficients as a function of timescale. (All regressions are more than .95% significant)

Timescale (years)	Mean Residual (m)	Regression Coefficient (a)	Sample Size
Erosional Event	1.6	0.69	68
1	1.5	0.82	9
2	2.2	0.77	7

offshore (Lee et al., 1998). Therefore, as timescale increases the influence of bar movement at depth changes little and deeper closures are related other processes such larger-scale cross-shore sediment redistribution or profile translation.

MODELLING DEPTH OF CLOSURE USING EQUILIBRIUM PROFILE THEORY

The analysis above gives insight into the factors which control closure. However, it also shows that the prediction of closure as a function of both depth change criteria and timescale is quite difficult with the existing range of tools. This section outlines how a general predictive approach might be developed based on recent improvements to equilibrium profile (EP) theory (see also Capobianco et al., 1997).

In many cases it is possible to describe a beach profile through simple analytical expressions derived from EP theory (e.g., Dean 1977, Inman et al. 1993, Larson and Wise 1998). These expressions contain empirical parameters that depend on the beach and wave characteristics. Therefore, profile dynamics can be predicted as a function of wave climate. Although such an approach involves considerable simplifications, it may provide a basis for a generalised statistical definition of the depth of closure that is more easily adapted to engineering use than existing methods. Figure 5 outlines a proposed modelling approach based on EP theory which takes account of all the key variables, including wave statistics, slope and grain size and could provide useful estimates of closure at all engineering scales (small, medium and large scales).

A preliminary investigation on the possible timescale dependency of the equilibrium profile was undertaken using wave data from Duck. A 13-year long time series of waves measured every 6 hr was used. The approach of Larson and Wise (1998) for non-breaking conditions was adopted to evaluate the EP using the wave climate resulting from a period ranging from one month to 12 years using steps of one month. Clearly the significance of the statistics for one month is lower than that for

The slower growth of observed closure than predictions using Equation 1 at timescales above annual may be related to bar migration. Annual closure is strongly related to cross-shore bar movement. However, cross-shore bar migration is constrained to the shore and the crest of the outer bar at Duck rarely moves more than 300 m

the statistics of twelve years; nevertheless we expect such an approach to give an indication of possible trends or of the possible changes of the EP. We expect such computations to be significant as the one month time-step is considered to be sufficient for the profile to respond to the most significant storms.

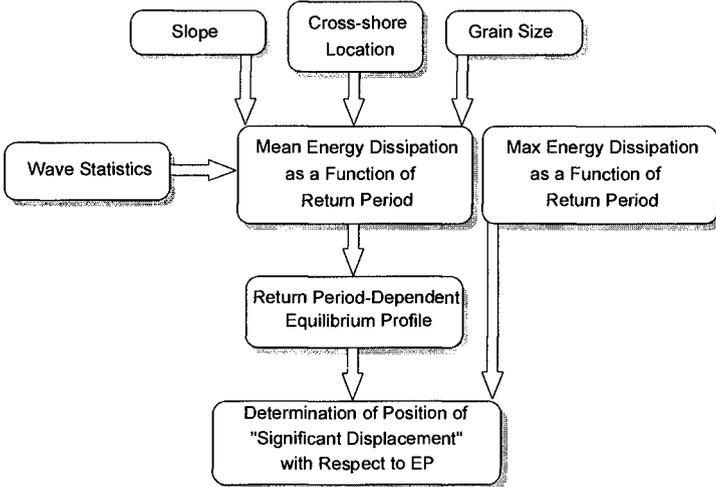


Figure 5. Proposed method to model depth of closure using EP theory

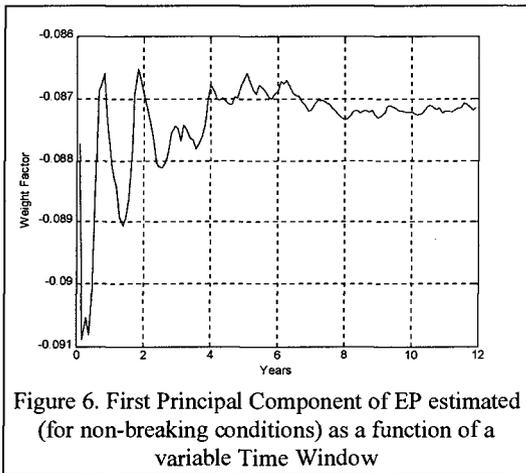


Figure 6. First Principal Component of EP estimated (for non-breaking conditions) as a function of a variable Time Window

The resulting EP data were analysed using Principal Component Analysis; in Figure 6 the behaviour of the First Principal Component is shown as a function of time. It is interesting to note that it stabilises after 4 years. While we must interpret such results with caution, from this simple analysis it appears reasonable to conclude that when the whole profile is considered an (engineering significant) EP requires several years to become established.

Larson and Wise

(1998) have derived a composite EP where the equilibrium shapes differ in the surf zone and offshore zone (compare Inman et al. 1993). The typical break point location separates the two zones; in the surf zone the Dean (1977) EP is employed, while in the offshore zone a lower exponent (0.3) is used. Two empirical shape parameters (A and B) define the composite EP: in the surf zone the shape parameter (A) depends primarily on grain size; and in the offshore zone shape parameter (B) depends mainly on the typical depth at breaking. Thus, if the characteristic wave conditions are known in the offshore, the break point may be calculated and the composite EP could be constructed from knowledge of the grain size. The composite EP includes one mobile bar related to the break point, and so captures some of the bar dynamics raised by Figure 1. For a series of offshore waves a corresponding series of EP may be computed from which statistical properties describing profile variability at different cross-shore locations can be derived.

In order to evaluate this method to compute profile variability, data from Duck was again employed. The time series of waves was used to compute the corresponding EPs for various values on the shape parameter B (A was set to 0.1, which approximately agrees with the grain size at the site -- 0.2 mm (see Larson, 1991)). The conditions at breaking were computed from the significant wave height and peak spectral period in the offshore using the formula given by Larson and Kraus (1989) and a ratio between wave height and water depth at breaking of 0.78. From the generated time series of EP the standard deviation was computed. Figure 7 displays this quantity for two different values of B and compares it with the standard deviation for profile lines 62 and 188 at Duck. While the qualitative form of the results is encouraging, they clearly illustrate that some aspects of the method need to be improved before reliable quantitative results can be obtained. For example, no attempt was made to translate the shoreline in response to changing wave conditions in the model leading to zero standard deviation at the shoreline in marked contrast to the data. Also, since the composite EP responds instantaneously to the wave conditions much more depth variation is predicted in deeper water than is observed. However, these two deficiencies in the model could be remedied by introducing a mobile shoreline (depending on the wave conditions) and a response function that takes into account the increasingly lagged response of the profile with depth. After the introduction of these features a simple EP based model may be used to theoretically determine the profile variability from which statistically defined depth of closures could be derived.

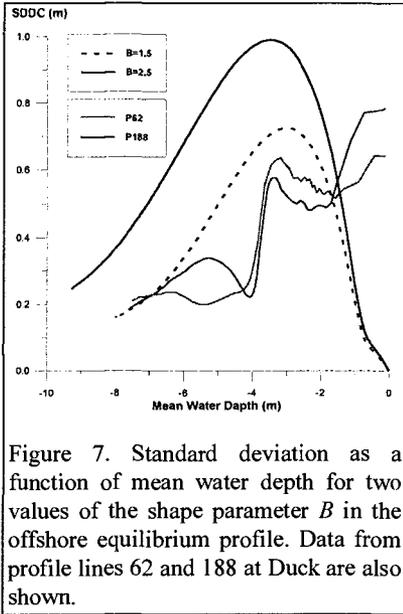


Figure 7. Standard deviation as a function of mean water depth for two values of the shape parameter B in the offshore equilibrium profile. Data from profile lines 62 and 188 at Duck are also shown.

CONCLUSIONS

Closure is a time- and space-scale dependent concept and hence, the controlling processes also vary with scale. Therefore, while closure is an empirically simple concept, its prediction remains difficult. For specific scales and circumstances, robust tools are already available. Equation 1 defines a limit to observations using a 6-cm depth change criterion for erosional events and at annual timescales, assuming limited net profile translation. As timescale increases above one year, so Equation 1 tends to increasingly overpredict the actual closure. This reflects a change in the processes that control closure from cross-shore bar migration to net gains and losses of sediment (and the resulting profile translation) and ultimately, shoreface processes. At sites with sufficient data, empirical methods to predict closure can

also be developed as a function of different depth change criteria. These relationships may be applied at other sites with caution. They also illustrate the utility of treating depth change as a variable which can be of benefit to endusers.

Further analysis is required and this includes continued data analysis and preparation of calibration datasets (cf. Table 1). In addition, new robust modelling approaches are required which can generalise the different factors which influence closure over the range of engineering timescales. The equilibrium profile theory approach presented here is one promising method for quantifying profile variability over these scales.

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