Assessment of Depth of Closure on a Nourished Beach: Terschelling, The Netherlands

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Abstract

Depth of closure is studied on a nourished beach in the light of its autonomous behaviour over long temporal and large spatial scales. Long term data show that depth of closure is variable alongshore, being shallower to the west and deeper to the east. Following placement of a shore nourishment along the middle section of the coast, the spatial variation of depth of closure changes. Initially the depth of closure is shallowest where the fill was placed. With time after the placement of the fill, this effect diminishes. Depth of closure observed in this study is influenced by bar behaviour. The fill material affects the observed depths of closure by reducing offshore bar migration. Maximum depths of closure for any particular timescale observed in this study are well predicted by the Hallermeier (1981) formulation for the depth limit to the active profile. In conclusion, pre-fill observations and Hallermeier (1981) provide a useful <u>*limit*</u> *to the observed post-fill depth of closure. Similar analysis of other beach nourishment projects would be useful.*

Introduction

Beach or shore nourishment is increasingly the preferred engineering solution when eroding coastlines require protection (Davison *et al*, 1992; Khabidov *et al*, 1996; Cooper, 1998). When designing a nourishment project it is important to have a detailed understanding of how the nourished coast will respond to the local hydrodynamic and morphodynamic regime. Furthermore it would also be useful to know whether placement of fill material will affect the local morphodynamic regime, even if the hydrodynamic conditions do not change. One fundamental aspect of the morphodynamic regime that has received increasing attention in recent years is depth of closure (Hallermeier, 1981; Nicholls *et al*, 1998).

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If a series of beach and nearshore profiles are collected at a given location, the profile will change through time. In any normal set of profiles, it will be clear that bed elevation is highly variable within the littoral zone. Moving offshore this variability decreases; consequently a plot showing several profiles collected over time will have a depth at which the profiles "close" within the accuracy of the data. In other words, the depth of closure represents the seaward limit of the profile envelope. Depth of closure is a morphodynamic boundary which separates a landward, morphodynamically active zone from a seaward, morphodynamically inactive zone over the period defined by the observations (Nicholls *et al*, 1996). Depth of closure does not represent a barrier to cross-shore sediment transport.

Depth of closure is a key design parameter in the design of beach or shore nourishments (Davison *et al*, 1992). Depth of closure allows coastal engineers to estimate how far offshore morphological change is likely to extend, and hence, calculate the volume of sediment required to nourish a section of coast. However it remains unclear if placing nourishment material influences depth of closure. To investigate this question, depth of closure on a nourished shoreline will be compared to depth of closure on the same shoreline prior to nourishment. Any changes that occur because of the placement of nourishment material can then be investigated. The study will also include an examination of the validity of the Hallermeier (1981) formulation for the depth limit to the active profile.

Study Area

This work focuses on data collected at the Dutch barrier island of Terschelling, figure 1. Two morphological data sets covering this site will be analysed; these are the JARKUS data set and the NOURTEC data set. The combined data sets cover a longshore distance of 12 km and span a time period of 30 years from 1965 to 1995.

The JARKUS data set is comprised of annual surveys along the whole of the Dutch coast. Data collection began in 1963 with annual surveys extending seaward 1200 m. Since 1965 there have been five-yearly surveys extending to 2500 m. Depth of closure tends to occur seaward of 1200 m, so in this study only the five yearly extended JARKUS data are used. The central section of Terschelling has suffered from severe shoreline erosion. In an attempt to overcome this problem, 2.1 million cubic metres of sand were placed in the nearshore zone, between the middle and outer bars of the triple barred system, figure 2. The nourishment sand was slightly coarser ($D_{50} = 200\mu m$) than the native sand ($D_{50} = 180\mu m$) at the point where the fill was placed. The sand grain size decreases across the profile from $220-260\mu m$ on the beach to $150-160\mu m$ on the lower shoreface, (Hoekstra *et al.*, 1994).

The nourishment was placed by RWS-RIKZ, the Dutch National Institute for Coastal and Marine Management and was monitored under the European Community Marine Science and Technology (MAST), Innovative Nourishment Techniques Evaluation (NOURTEC) programme. The length of the nourishment was 4.4 km (from 13.7 km to 18.1 km). Its placement depth ranged from -5 to -7 m NAP (NAP is Dutch Ordnance Datum; zero NAP is approximately mean sea level), Hoekstra *et al* (1996). Many previous nourishment projects have been criticised for failing to monitor the fill response adequately after placement; see Davison *et al*, (1992). The Terschelling nourishment has been surveyed in considerable detail following its placement. Ten surveys were carried out with one in spring 1993, immediately prior to the fill placement and nine after placement of the fill between autumn 1993 and winter 1995. Dates of surveys and survey reference numbers are shown in table 1.

The survey area is approximately 25 km^2 , and surveys extend from the top of the dunes backing the beach to 2 km offshore, at a water depth of 9 to 10 metres. The spring tidal range is 2.8 m, and the average annual significant wave height is approximately 1.5 m (associated wave period 8 seconds). Severe winter storms can generate waves up to 6 m high (period 10 - 15 seconds); the highest waves are typically from the northwest.

Survey Date	Survey Number
19 May 1993	1
17 November 1993	2
11 January 1994	3
20 April 1994	4
14 June 1994	5
10 October 1994	6
2 December 1994	7
10 March 1995	8
7 September 1995	9
13 December 1995	10

Table 1: NOURTEC Survey dates and survey numbers.

Previous studies (Ruessink and Kroon, 1994; Ruessink, 1998) show that the bars normally migrate offshore and similar morphology recurs about every 12 to 15 years. Ruessink (1998) shows that ebb tidal shoals are present at the eastern and western ends of Terschelling and it is possible that tidal inlets influence the profiles at the eastern end of the study area.

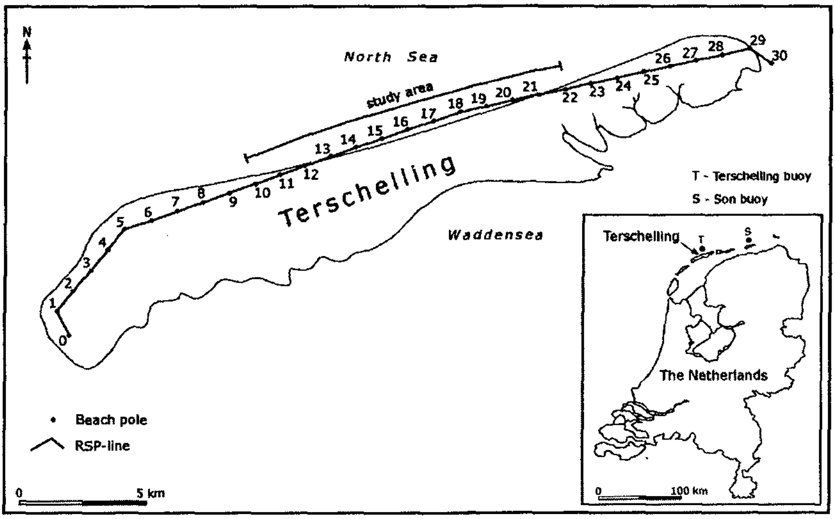

Figure 1. Location map showing the barrier island of Terschelling on the Northern Holland coast and the location of the study area.

The NOURTEC profiles were collected along the same transect lines as the JARKUS profiles. The combined use of JARKUS data and NOURTEC data means that depth of closure in an artificially forced situation can be compared with the autonomous behaviour of closure over the preceeding 25 years.

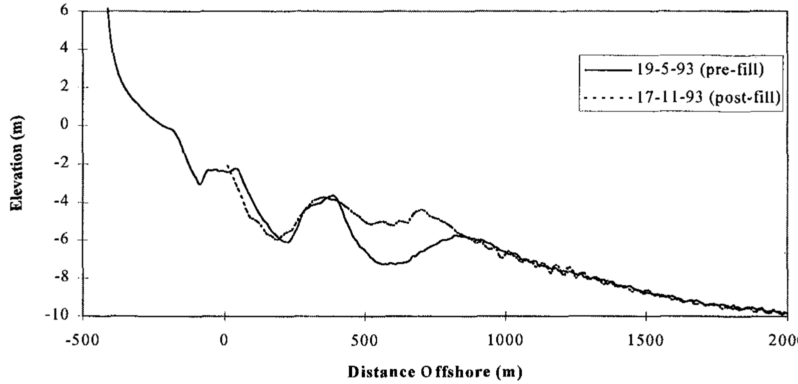

Figure 2. The fill material was placed between the middle and outer bars of a triple barred system.

Quantifying Depth of Closure

Closure occurs at a depth below which there is no measurable change in bed elevation, so measurement accuracy defines the criteria used to recognise closure in field data. In this study two techniques for determining depth of closure will be used; these are the standard deviation of depth change (SDDC) technique and a fixed criteria technique.

Standard Deviation of Depth Change (SDDC) Technique

For any given point that has been repetitively surveyed, it is possible to calculate the standard deviation of depth through time. When these standard deviation values are plotted along surveyed lines it is possible to discriminate between variability due to true changes in depth and variability that is due to measurement error (Kraus and Harikai, 1983). When the variability is due to measurement error alone, the profiles can be considered closed for the time period concerned. In the JARKUS data set, the standard deviation of depth typically falls to a non-zero tail with a value of approximately 0.25 m for profiles which exhibit closure. The mean depth at the beginning of the non-zero tail is defined as the depth of closure.

Fixed Criteria Technique

When two profiles are taken at the same location at different times it is possible to calculate the difference between the profiles along their length. When the difference falls below some value (determined by the accuracy of the data) then the profiles can be considered closed. We can assume that the JARKUS data measurement errors are normally distributed, and as stated above, these errors have a standard deviation of about 0.25 m. This means that if we observe a depth change of 0.25 m and 0.50 m between two profiles, then we can be 66% and 95% confident that a real change has occured, respectively. In this study a fixed criteria of 0.50 m will be used when calculating fixed criteria depths of closure (*cf.* Nicholls *et al.*, 1998). The depth of closure is then calculated by moving up the profiles from the seaward end, with closure being the mean depth where the difference between the profiles exceeds 50 cm.

Results

Pre-Fill Behaviour

Firstly, depth of closure for the whole JARKUS period will be examined using SDDC and fixed criteria techniques. SDDC profiles were constructed for lines 10 to 22 using JARKUS data for 1965, 1970, 1975, 1980, 1985 and 1990. The alongshore variation in depth of closure is shown in figure 3.

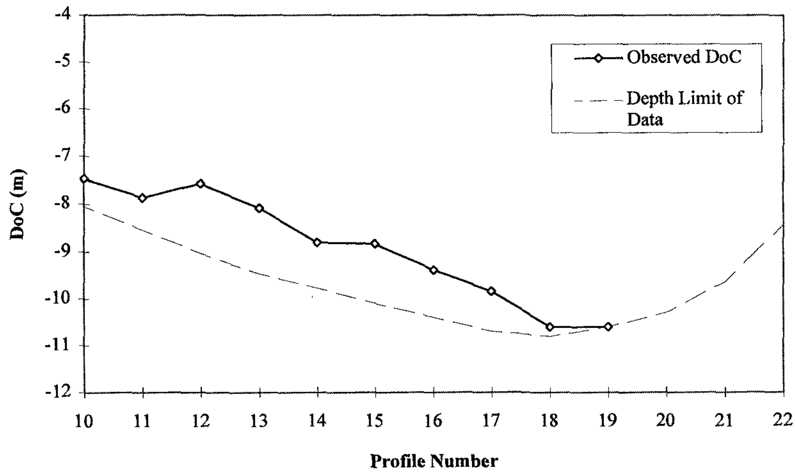

Figure 3. Observed longshore variation in depth of closure from 1965 to 1990, calculated using the SDDC method.

At the west of the island (lines 10, 11 and 12) the observed depth of closure is in the region of 7.5 to 8 m. This increases to the east as far as line 19, where the observed depth of closure is 10 to 10.5 m. Lines 20, 21 and 22 do not exhibit closure. This is attributed to the profiles ending before the depth of closure is reached. The depth limit of the profiles is indicated on figure 3, and we infer that if closure occurs it is deeper than the maximum depth of the profiles. A tidal channel is also present at the east of the island, and this is likely to extend into the study area. The migration of this tidal channel may affect depth of closure, and hence morphological change is occuring which is not simply wave driven.

Depths of closure using the fixed criteria technique were calculated for each five year interval between JARKUS surveys, for each line in the study area. These are shown in figure 4. Again there is a trend for depth of closure to become deeper to the east of the island. The trend is significant at the 95% level for three periods: 1965-1970, 1970-1975 and 1975-1980.

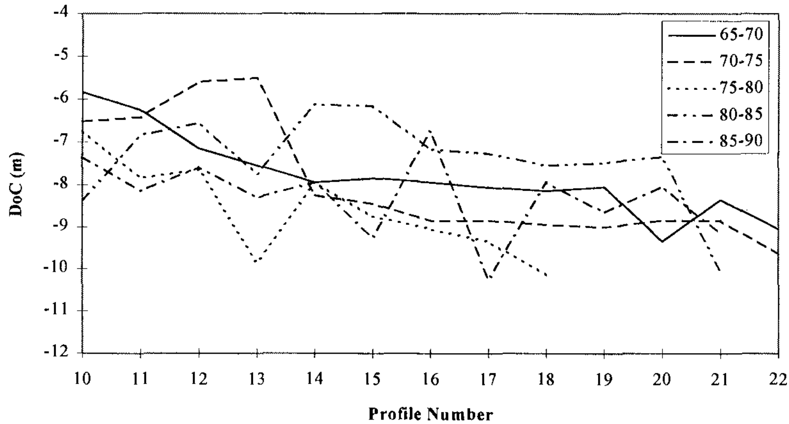

Figure 4. Observed depths of closure determined using a fixed criteria depth change criterion of 50 cm for five-year time intervals.

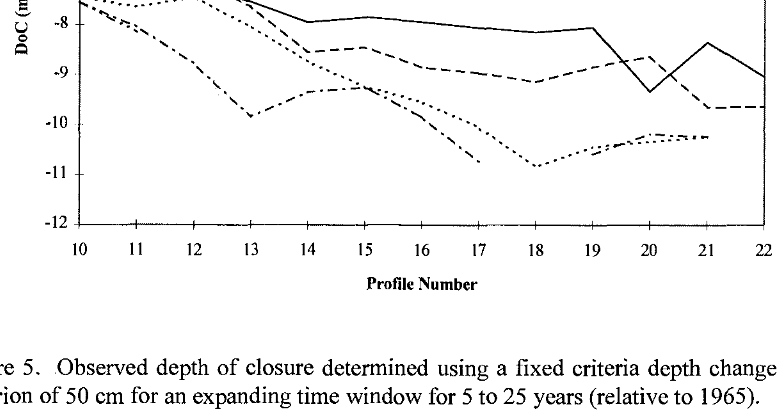

Figure 5. Observed depth of closure determined using a fixed criteria depth change criterion of 50 cm for an expanding time window for 5 to 25 years (relative to 1965).

If the timescale is increased the trend is similar, with deeper closure to the east. Figure 5 shows depth of closure for 5, 10, 15, 20 and 25 year time intervals using 1965 as the reference profile; the alongshore variation is significant at the 95% level for all of these time intervals. Depth of closure also tends to increase with timescale as has been observed at other sites, such as Duck, NC (Nicholls *et al*, 1998).

Post-Fill Behaviour

Using data collected as part of the NOURTEC project, post-fill depths of closure were calculated using the SDDC and fixed criteria techniques. The first pre-fill NOURTEC survey is excluded. Depths of closure calculated using the SDDC technique for the post-fill period are shown in figure 6.

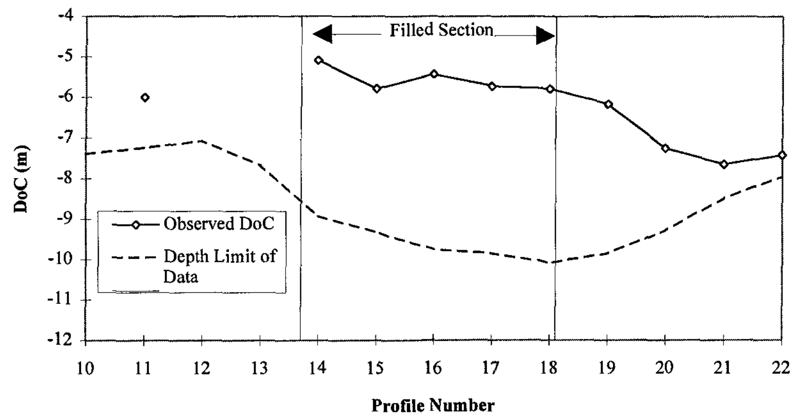

Figure 6. Observed longshore variation in depth of closure determined using the SDDC technique for the post-fill period (17th November 1993 to 13th December 1995).

The profiles for lines 10, 12 and 13 did not exhibit closure during the NOURTEC period. To give some representation of depth of closure at these locations, the depth limit of the profile data is shown. It is inferred that if closure does occur on these lines then it would be deeper than this depth. Interestingly the shallowest depth of closure occurs along the nourished section of the coast, which is quite different to the pre-fill behaviour (figure 3).

The depths of closure calculated using the fixed criteria method for each of the time intervals between NOURTEC surveys begin to explain the observed "average" behaviour shown using the SDDC method. Using the fixed criteria method, depth of closure still varies along the coast, but in general this variation does not show the systematic deepening to the east seen for the longer JARKUS periods which show shallow closure to the west and deeper closure to the east.

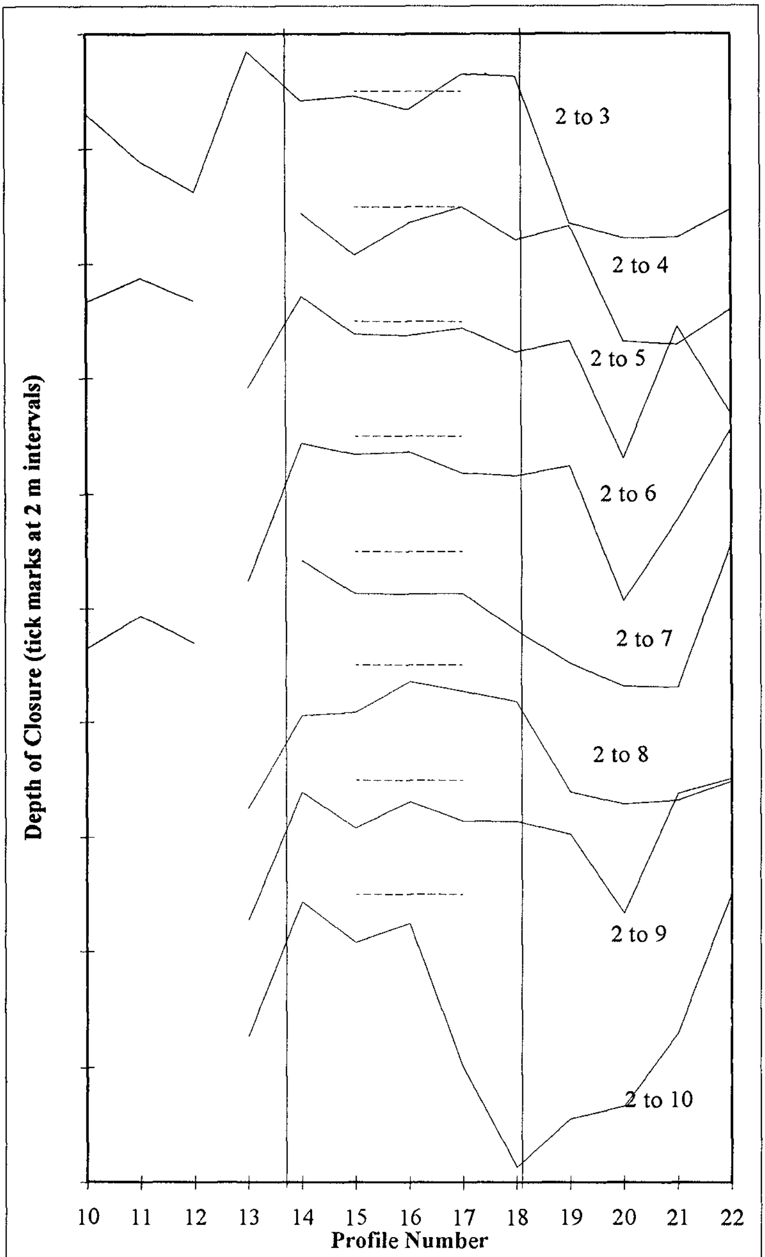

Figure 7. Time-expanding envelope, post-fill depths of closure. Intervals refer to survey numbers shown in Table 1. Each interval is offset by 2 m, and the dashed line indicates -5 m on each transect. The vertical lines mark the fill boundaries.

Depths of closure using a time-expanding envelope analysis were calculated to give a representation of the cumulative post-fill evolution of depth of closure. For these calculations the second NOURTEC survey (immediately after placement of the nourishment) was used as the reference.

The results of this analysis are shown in figure 7; the data are offset by 2 m for each survey to allow spatial patterns to be seen more clearly. Cases where no closure is observed are left blank. For most of the post fill period, there is a tendency for the shallowest depths of closure to occur in the nourished area, or just east of the nourished area. Westlake (1995) shows that sediment moved to the east following placement of the fill, and it is possible that this movement of sediment has an effect on the depths of closure observed.

Predicting the Depth Limit of the Active Profile

The depth limit to the active profile has been examined by Hallermeier (1981). Hallermeier proposed a predictive formula for the active depth limit which can be generalised to ($d_{\ell,t}$):

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

where $H_{e,t}$ is the significant wave height exceeded for 12 hours per t years and, $T_{e,t}$ is the associated wave period; g is acceleration due to gravity.

Evaluation of this method suggests that it provides a limit to actual closure during storms and for annual periods on wave-dominated, microtidal sandy coasts (Nicholls *et al*, 1996, 1998).

The wave data available in this study cover the end of the JARKUS monitoring period and the whole of the NOURTEC monitoring period. Wave data collection began at Schiermonnikoog (the Son buoy in figure 1) in 1979. The offshore buoy at this location is exposed to similar wave conditions to Terschelling (van Beek, 1995), and the wave data from Schiermonnikoog are used to calculate the depth limit predicted by equation 1 for the JARKUS data. The time intervals used for this calculation were 1980-1985, 1985-1990 and 1980 to 1990.

The depth limits predicted by Equation 1 for the NOURTEC data were calculated using wave data from the buoy located offshore of Terschelling (in 15 m water depth), and extend the analysis of Westlake (1995). The predicted depth limit, for each time interval between surveys, is compared with the observed depth of closure for each of the profile lines.

Figure 8a shows observed depths of closure plotted against the predicted depth limit for all data. The JARKUS data have a deeper predicted depth of closure than the NOURTEC data because they are based on a longer time interval. However, for both short and long timescales, the predicted depth limit based on a 12-hour exceedance wave height, acts as a good limit to the observed depths of closure. The range of

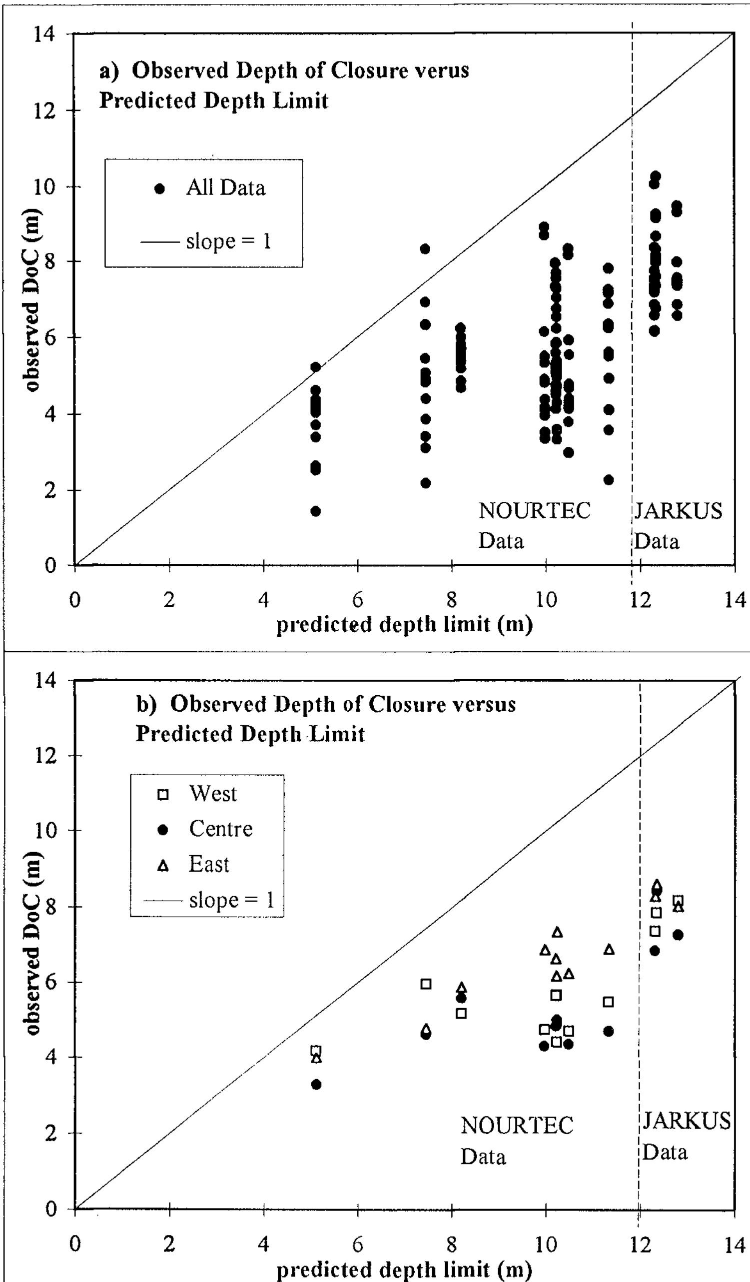

Figure 8. Observed depths of closure versus predicted depth limit of active profile. a) shows all data, b) shows average values for the western, central and eastern sections of the study area.

observed depths of closure for any measurement period is roughly constant at 4 metres. Hallermeier (1981) suggests that equation 1 approximates a yearly closeout of about 0.15 m using field data available in 1981. Nicholls *et al.* (1998) show that equation 1 is a limit to annual closure at Duck using a closure criteria of 6 cm. Therefore, using a 50 cm closure criteria, we would expect the observed depths of closure to be significantly shallower than equation 1 predicts (see figure 1, in Capobianco *et al*, 1997).

Figure 8b shows how the observed depths of closure vary in space, using the average observed depths of closure in the western, eastern and central sections of the study area (western is west of the fill boundary, the eastern section is to the east of the fill boundary; and the central section is the nourished section). It reinforces the observation of alongshore variation in the observed depths of closure.

Discussion

Equation 1 provides a limit to the closure observations which suggests that wave breaking is a fundamental control on the observed depth of closure (cf. Hallermeier, 1981; Nicholls *et al*, 1998). However it is also clear that depth of closure is variable alongshore. Assuming that the whole length of the shore is exposed to similar waves, then if the incident wave field were the only control over depth of closure we would expect depth of closure to be the similar along the whole coast. It is therefore likely that there are other controls on depth of closure along the Terschelling coast. In this study, the relatively large depth change criteria that has been used to define closure means that we may observe a depth of closure which is largely influenced by the outer bar position; it is the offshore migration of the outer bar that controls depth of closure. The depth change criteria of 50 cm used here would be expected to give shallower depths of closure than a 15-cm or 6-cm closure criteria, and we do not resolve some sub-50-cm morphodynamics in the profile that occurs deeper than our observed closures. However, using the data available gives us some understanding of how closure behaves over longer timescales than previous studies have investigated. This in turn allows more robust conclusions to be drawn regarding the influence that the nourishment has on the observed depth of closure.

Previous studies have shown that the migration of bars at Terschelling involves both longshore and cross-shore components of movement. The largest waves approach from the northwest and generate longshore currents to the east. Morphological studies (Ruessink and Kroon, 1994; Ruessink, 1998) show that bars propogate alongshore towards the east. There are ebb tidal shoals to the west of the island, and these are likely to protect the western section of the study area from the largest waves, hence the shallower depth of closure at the west of the island. In the centre of the island, the dominant process that is likely to affect the depths of closure observed in this study is cross-shore movement of the outer bar. Ruessink and Kroon (1994) show that the natural bar cycle involves a degeneration of the outer bar, and subsequent seaward migration of the middle bar. The return period of this cycle is approximately 12 to 15 years. An analysis of the furthest offshore position of the outer bar for the JARKUS data and the position of closure during the same time intervals shows that the position of closure is closely associated with the position of the outer bar as illustrated in figure 9. The observation of deeper closure to the east of the study area may be attributed to the presence of tidal channels which extend from the tidal inlets at the eastern end of the island, and hence produce tidally driven morphological change.

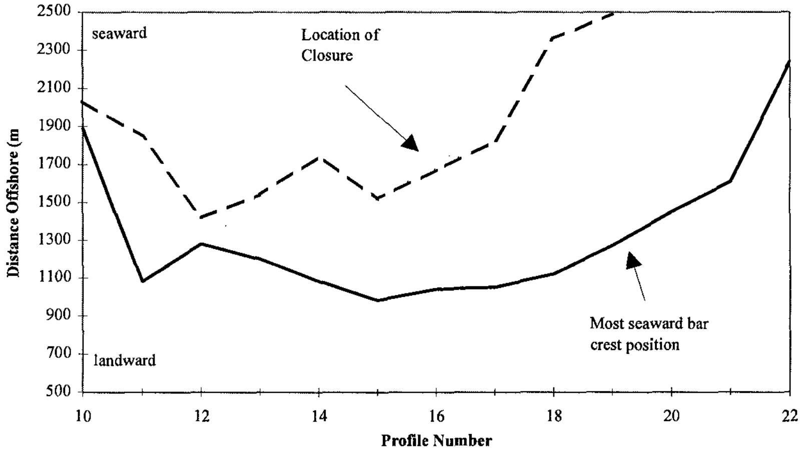

Figure 9. Location of closure (SDDC) in the JARKUS data and the most seaward bar crest position for the period 1965-1995.,

Given these observations, we are still faced with the question posed initially:

"What effect does the nourishment have on depth of closure?"

The long-term data suggest that depth of closure does vary alongshore, under natural conditions. However, the longshore variation of depth of closure is different in the post-fill period. In particular the mean behaviour, observed using the SDDC method, and the post-fill cumulative evolution of depth of closure, show that depth of closure is shallower than we would expect in the nourished area for the two year interval following placement of the fill. It appears that as the timescale considered increased, so the effect that the fill has on closure may diminish.

It has been suggested above that the closure we observe is influenced by bar migration. Assuming this is true, we then seek to explain how the fill has affected bar migration. The nourishment appears to have suppressed the offshore migration of the bar system, which might make the depth of closure we observe shallower than we might otherwise expect. Kroon *et al.* (1994) show that placement of the nourishment has decreased bar morphodynamics by making the middle bar stable in a position where it would have been expected to migrate offshore, based on observations before the fill.

Ruessink and Kroon (1994) argue that if the outer crest height is greater than about 5.5 m then on- and off-shore bar driving forces are balanced. Placing the fill between two crests effectively provided a much broader area to dissipate wave energy.

It also means that much more sediment had to be moved before cross-shore movement of bars could occur.

Westlake (1995) shows that after the nourishment sediment moved to the east and towards the land at the eastern end of the fill. Figure 7 shows that the section of coast with the shallowest closures migrates eastwards for much of the two-year period following fill placement. It is likely that the buffering effect that the fill has on bar migration also moves eastwards because of this *en masse* transport of material. However, the outer bar height is not diminished sufficiently for the middle bar to move offshore and take up the outer bar position in the time period for which we have observations.

The observation of shallower closure in the fill area in the short time period following placement of the fill is surprising. Based on first principles, the opposite behaviour would be expected because the fill would be expected to oversteepen the profile. In this case, the fill doesn't oversteepen the profile because it was placed in a trough between bars. On the basis of the observations of shallower closure in the nourished area, it is possible that placing the fill between the bars reduces the rate of loss of sediment from the nourishment site to the offshore zone in the period following placement of the fill. To assess the impact of the fill over long time periods, it will be necessary to examine data from the study area for at least one natural bar cycle period, approximately 12 years (Ruessink and Kroon, 1994).

Conclusions and Engineering Implications

Depth of closure is observed using SDDC and fixed criteria techniques over short and long time periods off the coast of Terschelling. Depth of closure observed in this study tends to vary systematically alongshore. Over long periods of time (5 years to 25 years), depth of closure is in the range 4 to 10 m, and is shallower to the west of the island, and deeper to the east.

Our ability to *predict* depth of closure remains relatively poor, but for both long and short time intervals, the depth *limit* to the active profile suggested by Hallermeier (1981) is a good upper limit to the observed depths of closure for both the nourished and un-nourished profiles. The terminology as used by Hallermeier (1981) is deliberate; formulations such as Equation 1 should be considered as a *limit* to the depth of closure, and not as a prediction of depth of closure. In this study, the autonomous variation below the limit predicted by Equation 1 is attributed to large scale morphological features.

This analysis shows that closure is influenced by beach nourishment but in this case, the closure depth was reduced by the placement of the fill. Therefore, the historical perspective of the extended JARKUS data, or Equation 1 are both useful to determine a limit to the actual closure. However, they do not allow prediction of the actual closure in the post-fill period. It will be interesting to continue to monitor the profile development at this site over a complete bar cycle (12 years), to see if the placement of the fill has a lasting effect on the bar behaviour and depth of closure.

This study gives some confidence in using the depth of closure concept as part of beach nourishment design. However, it represents one site and systematic monitoring of beach fills should be encouraged to extend our understanding of a wider range of situations (eg. Stauble and Grosskopf, 1993). As technology improves we look forward to more accurate vertical resolution, and the ability to resolve closure using smaller depth change criteria.

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