Spatial and Temporal Behaviour of Depth of Closure along the Holland Coast

Claire Hinton[*] and Robert J. Nicholls[*]

Abstract

Depth of closure has been identified and its characteristics investigated over larger temporal ($\geq$ 25 years) and spatial (< 100 kilometres) scales than previous research. In addition to the 'normal' shoreward closure produced by breaking waves and cross-shore bar migration, at longer timescales ($\geq$10 years) shoreface morphodynamics also produce significant profile changes. The shoreward closure is primarily controlled by wave breaking with a secondary control of bar morphodynamics. Shoreface changes are slow and steady and as timescale increases, so more profiles exhibit re-opening in depths typically greater than 10 metres. This is then usually followed by the re-closure of the profile on the middle/lower shoreface. Such phenomena have not been observed in past studies of this type and result from the large temporal and spatial extent of the data set used here. Over long time scales ($\geq$ 10 years) such changes have a coastal engineering significance.

Introduction

The application and scope of coastal engineering schemes i.e. shore protection and land reclamation, is increasing. For example, the present Dutch coastal policy is to maintain its coastline at its 1991 position for the foreseeable future. In order to ensure the long-term reliability of such projects it is vital that coastal evolution over the same temporal scale is understood. So, with the advent of focused research within this field, many relevant concepts are being developed through both observation and predictive techniques.

[*]Flood Hazard Research Centre, Middlesex University, Queensway, Enfield, Middlesex, EN3 4SF. United Kingdom

A key concept in beach morphodynamics is depth of closure (Dc). Dc represents the 'seaward limit of '*significant*' depth change' (Nicholls *et al*, 1996); it does not, however, refer to an absolute depth beyond which there is no cross-shore sediment transport. Therefore, it is seen to act as a morphodynamic boundary separating a landward, morphodynamically active region from a more seaward inactive region, where vertical changes are less than the criterion chosen to define closure. (Figure 1.)

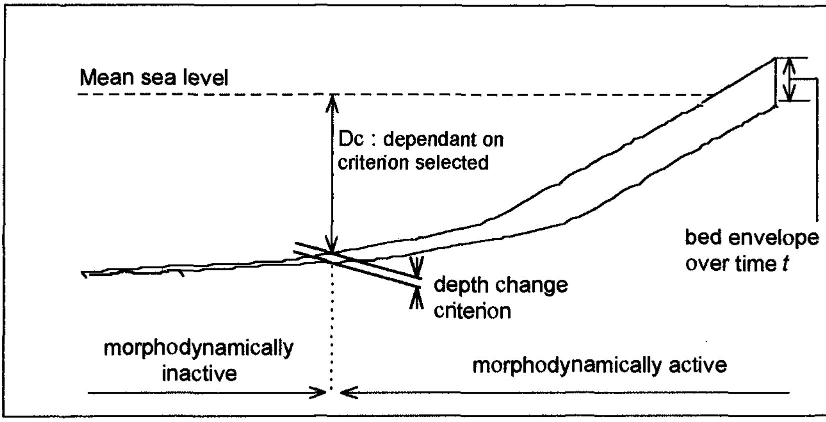

Figure 1. Zonation of a cross-shore profile over time *t* where Dc represents the seaward limit of significant depth change using the depth change criterion shown (adopted from Hallermeier, 1981).

Dc is of fundamental importance in coastal sediment budgets and associated applications such as beach and shoreface nourishment. Specific examples of its use are; i) as a boundary between active and inactive zones it allows for the correct placement of offshore mounds; location in the active region could provide material for onshore feed (Hands and Allison, 1991); and ii) as the limit of morphological change enabling the volume of beach fill material to be calculated (Davison *et al*, 1992).

In this paper the Large Scale Coastal Evolution concept of Stive *et al* (1990) is used to distinguish different scales of closure behaviour. The three scales are i) Large-Scale which has a morphodynamic length scale of 10 km and time scale of decades; ii) Medium-Scale with a morphodynamic length scale of 1 km and time scale of years; and iii) Small-Scale which has a morphodynamic length scale of 100 m and time scale of storms to seasons.

Closure has previously been investigated on the Medium-/Short-Scale (Garcia *et al*, 1997; Nicholls *et al*, 1996, 1998; Nicholls and Birkemeier, 1997). For example the Duck, North Carolina data has a 12 year time span and extends 1.2 km alongshore and 0.8 km cross-shore (Nicholls *et al*, 1996). These investigations have shown that Dc is time- and space-scale dependant (cf. Capiobianco *et al*, 1997). In particular, as the time interval increases then closure increases in depth.

The control of the extreme wave conditions upon closure is used in the analytical Hallermeier (1978) model to predict Dc. It has been adapted to a time-dependant form:

$$d_{l,t} = 2.28 H_{e,t} - 68.5\left(\frac{H_{e,t}^{2}}{gT_{e,t}^{2}}\right) \tag{1}$$

where: $d_{l,t}$ = closure (Dc) (referenced to MLW);
$H_{e,t}$ = significant wave height exceeded 12 hours per t years;
$T_{e,t}$ = associated wave period; and
g = acceleration due to gravity.

Field validation of Equation 1 has shown that it provides a *limit* to the observed closure on micro-tidal, wave-dominated, sandy coasts during i) storms; and ii) annual periods (Nicholls *et al*, 1996, 1998). This suggests that spatially similar regions of closure will exist; a less energetic hydrodynamic environment will result in shallower closure values than those in a more energetic environment (cf. Marsh *et al*, 1998).

Most closure studies are limited to the surf zone and upper shoreface due to survey constraints (a maximum depth of 8m is reached at Duck, North Carolina; Lee *et al*, 1998). The JARKUS data set used here offers the opportunity to extend analysis to the Large-Scale; 100 km alongshore, 25 years (1965 to 1990) and 16 m depth. In addition this will allow the existence of '*significant* depth changes' on the shoreface at depths exceeding previous observations of closure to be investigated (as previously recognised by Stive *et al*, 1990).

Study Area

The study area is the Holland coast bound from Den Helder in the north to Hoek van Holland in the south. (Figure 2.) It is a closed coast uninterrupted by tidal inlets or barrier islands, allowing the determination of Dc characteristics in a wave-dominated, alongshore uniform environment. Anthropogenic interventions are mainly smaller-scale beach nourishment schemes, although the Petten sea dike (km 20 - 26) and Ijmuiden harbour moles (km 55/56) are present in the north and centre of the coast, respectively.

The study area is a micro-tidal, wave-dominated sandy coast with multiple bars. The bars extend to a maximum depth of approximately 8 m. The mean tidal range is 1.4 m in the north increasing to 1.7 m in the south. Peak tidal velocities generally do not exceed 1 ms^{-1}. The annual mean wave height is 1.2 m (associated wave period 5 sec); whilst the extreme annual wave height is 5.3m (associated wave period 7.7 sec) (Roskam, 1988). The wave climate is relatively similar along the length of the coast, deviations in wave height from north to south are in the order of 0.2 m.

Cross-shore bathymetric measurements have been measured by the Rijkswaterstaat since 1963 at regular, fixed locations alongshore. The measurements are held within the JARKUS data set. They have a vertical accuracy of 0.25 m which is the standard deviation of the measurements, as determined within this study. An independent study, using both stochastic and systematic error sources, has also determined the accuracy of the data to be 0.25 m (Nanninga, 1985). Annual (short) profiles extend 0.8 km seaward, equivalent to a depth of approximately 6 m, with alongshore spacing of 0.25 km. In addition there are five-yearly long profiles ('doorlodingen') which extend to a minimum 2.5 km seaward, equivalent to approximately 15 to 16 m depth, and have an alongshore spacing of 1km. (Figure 3.) It is due to the greater cross- shore extent of the doorlodingen that it is analysed in this study; primary analysis indicates that Dc is not observed in the annual data even over a 1 year period. In addition, the most northern and southern profiles are rejected due to the tidal influence of the Marsdiep and the Europort inlets, respectively. The total study area therefore covers an alongshore distance of 81 km (km 16 to 97; Figure 2).

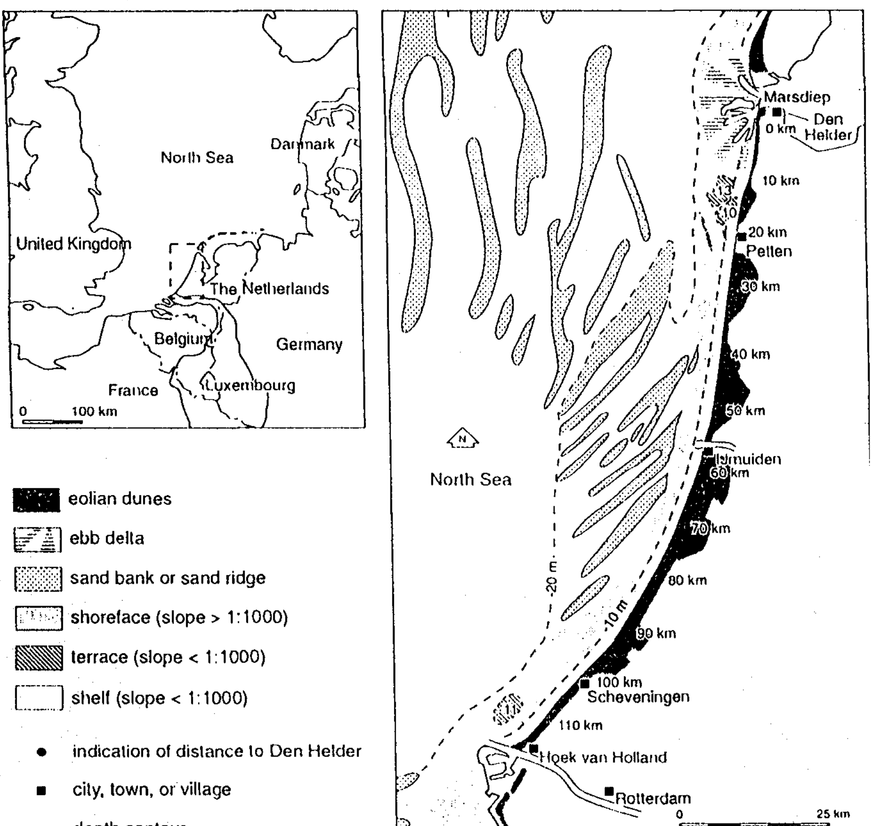

Figure 2. Location map showing the closed Holland coast. (Wijnberg, 1995)

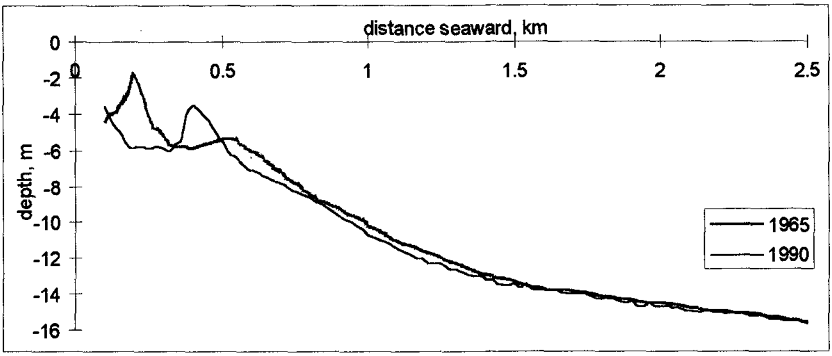

Figure 3. Example of the bathymetry along the closed coast using the doorlodingen from 1965 and 1990, located at km 31 (Noord-Holland).

Data Analysis

Values of Dc have been derived using two methods: i) the standard deviation of depth change (Kraus and Harikai, 1983) and ii) the fixed depth change (Nicholls *et al*, 1996). This analysis has been performed for all profiles over a range of temporal periods, 5, 10, 15, 20 and 25 years.

Standard deviation of depth change (sddc)

This is a simple method, effective in both dealing with large data sets and removing bias from outlying values. Variation in the standard deviation of elevation is shown as a function of the cross-shore distance for *x* number of profiles from the same alongshore location. Dc is then equated to that point at which the standard deviation reaches a constant, non-zero tail, which often has a value of about 0.25 m (the measurement accuracy). (Figure 4.)

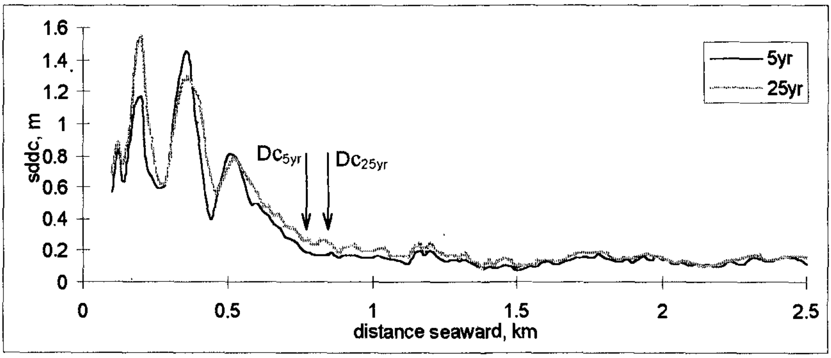

Figure 4. Sddc for km 31 which exhibits closure at a seaward distance of approximately 0.8 km for all time periods. ($Dc_{5yr} \approx$ 8 m depth; $Dc_{20yr} \approx$ 9 m depth)

Fixed depth change (fdc)

Dc can also be equated to that point at which, for 2 profiles from the same location, the depth variation is equal to, or less than, a pre-selected criteria. Here two criteria are selected: 0.25 m and 0.5 m. This means that there is 66% and 95% confidence that a real change in the bathymetry has occurred, respectively, assuming that the data measurement errors are normally distributed with a standard deviation of 0.25 m.

Results

General

Both methods produce similar results for all profiles along the Holland coast; the fdc criteria of 0.5 m generally gives the more landward value of closure as it allows the greatest depth variation.

Upon the examination of all results it became apparent that, in some instances, not only does the profile close at some distance x from the shore, but the profile re-opens and then usually re-closes towards its seaward limit. Such behaviour can be most clearly seen using the sddc plots. (Figure 5.) These phenomena are hereafter termed i) the shoreward closure (Dc_s); ii) the re-opening point (Ro) and associated re-opening zone; and iii) the middle/lower shoreface closure ($Dc_{m/l}$), respectively. Re-opening is only observed over the longer time scales (>10 years) and at distances offshore greater than 1.5 km (typically 12 m water depth). In addition, as the temporal period is increased the number of cases in which this behaviour occurs increases (18% of profiles re-open after 10 years increasing to 37% over 20 years).

Large-Scale Behaviour

All three 'modes' of behaviour only exist in temporal periods greater than one decade; therefore the observed behaviour during the 20 year period will be concentrated on here. The results from both methods show similar spatial behaviour. (Figure 6.) However, the sddc method does give a greater proportion of profiles which do not close; as sddc depends on a self-selecting non-zero tail, it was hard to extract exact values of the re-opening zone and middle/lower shoreface closure using this method. A fixed non-zero tail could overcome this problem and may be used in subsequent analysis.

Shoreward closure

It is apparent in Figure 6 (a) and (b), that two distinct alongshore regions exist. The first is in the north (Noord-Holland), and can be sub-divided into two; km 16 to 24 and 25 to 54 where Dc_s is quite deep ($\bar{x}$ = 8.5 m) and irratic. In the south (Zuid-Holland), km 55 to 97, a different regime is observed; Dc_s is shallow ($\bar{x}$ = 5.0 m) and relatively

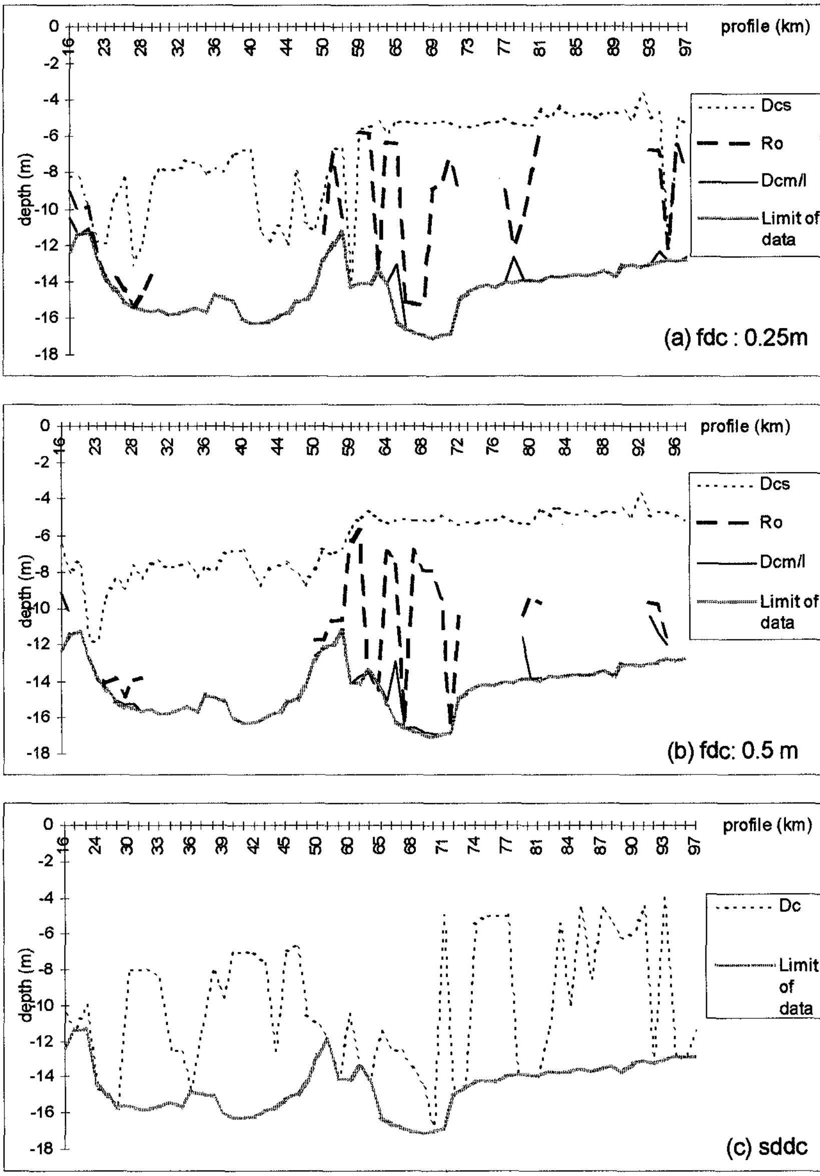

Figure 6. The spatial characteristics of the shoreward closure (Dc_s), re-opening point (Ro) and middle/lower shoreface closure ($Dc_{m/l}$) over 20 years using (a) fdc analysis (criteria 0.25 m); (b) fdc analysis (criteria 0.5 m), and (c) sddc analysis. The seaward limit of the data set is also shown.

constant in depth. (Table 1.) Interestingly, the regions observed here are bound by the two major anthropogenic influences on this coast; the Petten sea dike (km 20 - 26)and Ijmuiden harbour moles (km 55/56).

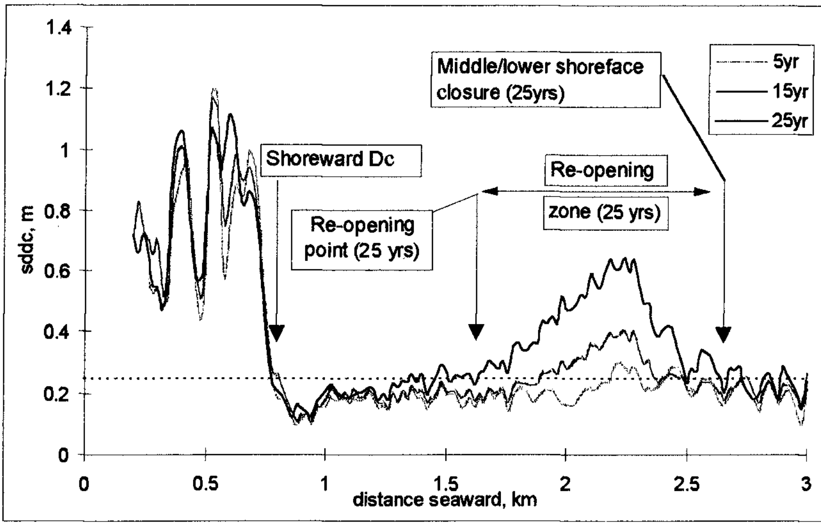

Figure 5. Sddc at km 69 which exhibits re-opening and subsequent closure for time periods of 15 and 25 years.

REGION	MEAN DEPTH (m)	STANDARD DEVIATION (m)
1) km 16 - 24	9.2	2.2
2) km 25 -54	7.7	0.6
3) km 55 - 97	5.0	0.3

Table 1. Characteristics of the shoreward closure over 20 years in the 3 regions, as given by the fdc criteria of 0.5 m.

Application of Hallermeier (1978)

The shoreward closure can be compared with a value calculated using Equation 1. The input data is a time series of wave heights and associated periods measured over a five year period at a station offshore from Ijmuiden, in 18 m water depth. Given the alongshore similarity of the wave climate this is a reasonable comparison for all observed Dc_s. The calculated value for this study is 9.2 m (relative to MLW) over a 5 year period (1980 to 1985). (Hydrodynamic data is insufficient at present to allow calculation over a 20 year period.) This predicted value is a limit to the observed value over the same period, and over 20 years (Table 1), and is consistent with the behaviour observed in earlier studies and Marsh *et al* (1998).

Re-opening and middle/lower shoreface closure

The re-opening zone represents a 'significant' depth change on the shoreface, as defined by the criteria selected. This behaviour is typically followed in the cross-shore by middle/lower shoreface closure. Those instances in which it does not re-close may result from data limitations. It is hypothesised that if the measurements were extended in the seaward direction then re-closure would be observed.

Re-opening does not occur along the whole of the Holland coast. (Figure 6.) It occurs in four alongshore zones defined in Table 2.

RE-OPENING ZONES	MEAN DEPTH (m)	STANDARD DEVIATION (m)
1) km 16 -29	13.0	1.9
2) km 47 - 72	10.3	3.4
3) km 77 - 81	9.8	0.5
4) km 91 - 92	10.0	1.1

Table 2. Characteristics of the re-opening point by longshore zone, over 20 years, as given by the fdc analysis (using a 0.5 m criterion).

Discussion

General

This data has shown a shoreward closure in 5 m to 8 m depth similar to that observed at other sites such as Duck, North Carolina (Nicholls *et al*, 1996, 1998). As the time scale increases it has also shown *significant* profile changes seaward of this shoreward closure.

Shoreward closure

Dc_s appears to be primarily a function of sediment movement under extreme breaking waves (cf. Nicholls *et al*, 1996). Comparison of closure predicted with Equation 1 and that observed on the Holland coast suggests that this is also true here. These preliminary calculations show that Hallermeier (1978) can be used as a predictive tool for the seaward *limit* of Dc_s along the Holland coast. Similar results have also been observed in past studies; at Terschelling, The Netherlands (Marsh *et al*, 1998) and Duck, North Carolina (Nicholls *et al*, 1996, 1998). Interestingly, Dc_s does not appear to increase with time scale as rapidly as Equation 1 would suggest.

Alongshore variation of closure defines two main regions; i) Noord-Holland, which can be further sub-divided into two, and has a mean closure of 8 m; and ii) Zuid-Holland which has a mean closure of 5 m. This indicates that processes, in addition to extreme waves, exist which play a role in the morphological behaviour of the active zone over time scales greater than 5 years. Other factors which have been shown to be of some importance in past studies are i) pre-event outer bar volume (at the Small-Scale); and ii) sediment budget (at the Middle-Scale) (Nicholls and Birkermeier, 1997).

Scale); and ii) sediment budget (at the Middle-Scale) (Nicholls and Birkermeier, 1997). Wijnberg (1995) classified the Holland coast using bar behaviour, defined using eigenfunction analysis which shows both i) the different time scales of active bar behaviour; and ii) the along- and cross-shore migratory behaviour. For the area studied here, three regions of similar behaviour were observed; 1) km 16 - 23; 2) km 24 - 55; and 3) km 57 - 97. These directly correlate with the three regions identified using Dc_s. (Figure 7).

The multiple bars in Holland migrate offshore at different rates and ultimately disappear; the morphological cycle repeats every 15 years in regions 1) and 2) (Noord-Holland) and every 4 years in Zuid-Holland. The degeneration of the outer bar in the Noord-Holland system occurs at a greater depth than in Zuid-Holland. This agrees with the greater closure depths observed in Noord-Holland as compared to Zuid-Holland. It is therefore concluded that shoreward closure is primarily controlled by extreme breaking wave conditions with the bar morphodynamics acting as an additional control, similar observations have been made on the meso-tidal barrier island of Terschelling, The Netherlands (Marsh *et al*, 1998).

Re-opening and middle/lower shoreface closure

This behaviour has not been systematically observed in previous studies. Activity on the shoreface has, however, been recognised in past studies (Stive *et al*, 1990), although the processes which control this behaviour are poorly understood. The occurrence and size of the re-opening zone is seen to be time-dependant; as the time period increases, the extent (both in the cross-shore distance and degree of depth variation) steadily increases. This suggests that this behaviour is due to slow, cumulative change, rather than fast, infrequent events. Indeed, the middle/lower shoreface behaviour has been indicated to be morphodynamically weakly varying (Stive *et al*, 1990). In most cases the re-opening is associated with a local shoreface steepening. Roelvink and Stive (1990) and Stive *et al* (1990) have shown that the significant depth change observed on the shoreface represents the effect of the onshore transport of material to the active zone. The specific location of this phenomena within four zones along the Holland coast may help towards the identification of the controlling processes; at present only tentative correlations between process and response have been made. It is expected that this behaviour will be related to hydrodynamic parameters, as with the shoreward closure. It is hypothesised that it is the asymmetry of shoaling waves which are the primary influence, with an additional forcing introduced by tidal and wind- induced currents, which become more significant in the offshore (Komar, 1976; Stive *et al*, 1990).

In addition the two major anthropogenic structures along the closed coast, the Petten sea dike (km 20 - 26) and Ijmuiden harbour moles (km 55/56), are located in the two largest re-opening zones, km 16 -29 and km 47 - 72 respectively. These can influence offshore behaviour. The Ijmuiden harbour moles, which are 2.5 km in length, have influenced tidal excursion and so accretionary/erosive behaviour for substantial distances, tens of kilometres, from the structure (Roelvink *et al*, 1998). Other morphodynamic controls should be considered. For example, shoreface-connected ridges are present from km 45 - 65 (Van de Meene, 1994); coinciding with the occurrence of re-opening. These ridges are mapped to minimum depths of 14 m although they may occur further onshore.

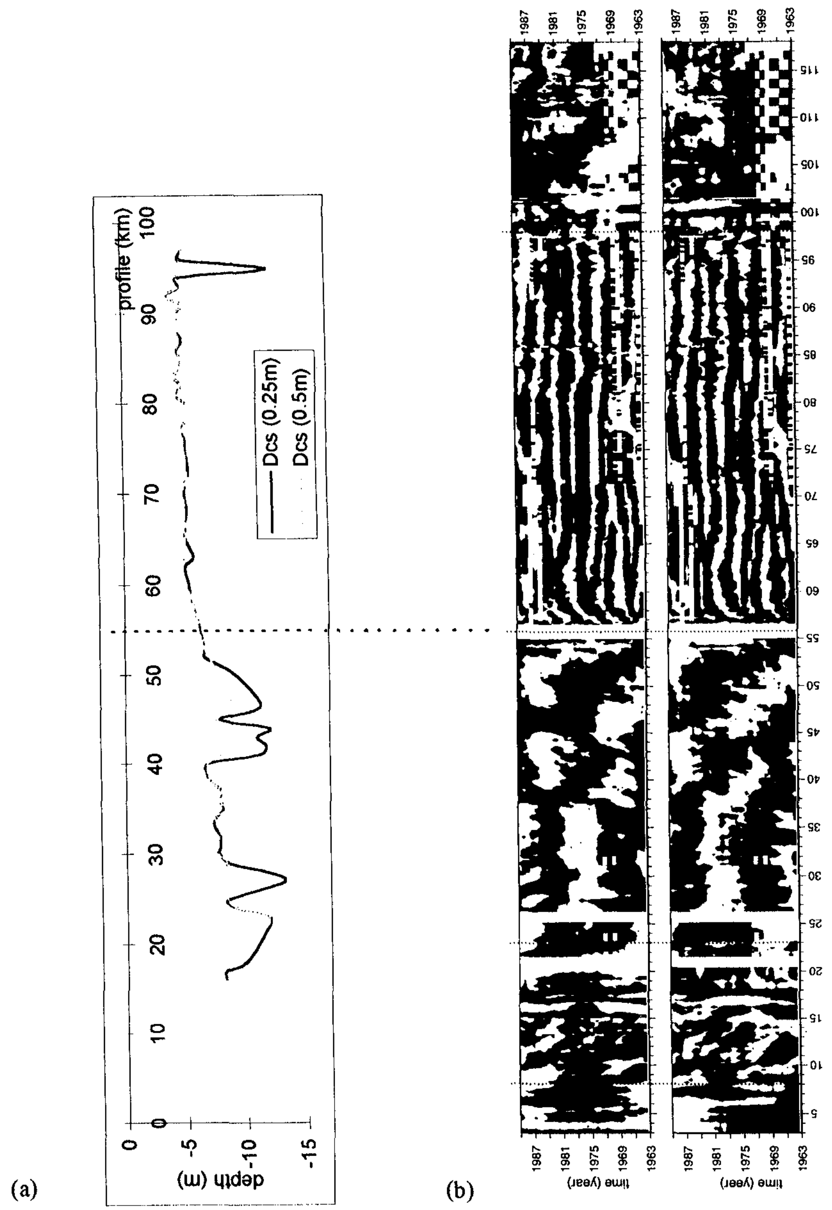

Figure 7. Alongshore correlation between the shoreward depth of closure (a) and bar behaviour (b) (as defined by eigenfunction analysis; Wijnberg, 1995).

Conclusion

The large temporal and spatial extent of the JARKUS data set has enabled Large-Scale closure behaviour to be determined. The profile closes at depths of 5 m to 8m (shoreward closure). In addition, as the time scale increases *significant* profile changes are observed in four alongshore zones seaward of the shoreward closure; re-opening of the profile occurs and is typically followed in the cross-shore by middle/lower shoreface closure. All of the observed characteristics are temporally dependant.

Shoreward closure shows alongshore variation with deeper values observed in the north. It is hypothesised that Dc_s is primarily under the control of wave breaking, as seen by the generalised value given by the Hallermeier (1977, 1981) formulation. An additional control is imposed by bar behaviour (Wijnberg, 1995). Profile re-opening and the subsequent middle/lower shoreface closure is identified in four distinct zones along the closed coast. The possible hydrodynamic, morphodynamic and anthropogenic controls are being investigated.

In addition to the obvious engineering applications of closure, e.g. for the calculation of beach fill volumes, the occurrence of the re-opening zone reminds users that *significant* depth changes can occur seaward of the shoreward closure. It is vital that this is taken into consideration by engineers, especially over decadal and longer time scales.

Acknowledgements

This work was carried out as part of the PACE project, within the EU sponsored Marine Science and Technology programme (MAST-III) under contract number MAS3-CT95-002. The JARKUS data set is collected by Rijkswaterstaat/RIKZ (the Dutch National Institute for Coastal and Marine Management) and made available within the PACE project. The authors would like to thank all those involved in its collection and processing.

References

Capiobianco, M., Larson, M., Nicholls, R.J., and Kraus, N.C., 1997. Depth of closure: A contribution to the reconciliation of theory and practise. Proc.Coastal Dynamics '97. ASCE, New York. pp. 506 - 515.

Davison, A.T., Nicholls, R.J., and Leatherman, S.P., 1992. Beach nourishment as a coastal management tool: An annotated bibliography on developments associated with the artificial nourishment of beaches. Journal of Coastal Research, 8(4), pp. 984-1022.

Garcia, V., Jimenez, J.A., and Sanchez-Arcilla, A., 1997. Temporal and spatial variability of the depth of closure in the Ebro delta. First Annual PACE Workshop, Abstracts-In-Depth, Abstract #1.4, 4pp.

Hallermeier, R.J., 1978. Uses for a calculated limit depth to beach erosion. Proc. 16th Coastal Engineering Conf., ASCE, New York. pp. 1493 - 1512.

Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. Coastal Engineering, 4, pp. 253-277.

Hands, E.B., and Allison, M.C., 1991. Mound migration in deeper water and methods of categorising active and stable depths. Proc. Coastal Sediments '91, ASCE, New York. pp 1985 - 1999.

Kraus, N.C., and Harikai, S., 1983. Numerical model of shoreline change at Orai beach. Coastal Engineering, 7, pp. 1-28.

Komar, P.D., 1976. Beach processes and sedimentation. Prentice-Hall, Englewood Cliffs, New Jersey, 429pp.

Lee, G., Nicholls, R.J., and Birkemeier, W.A., 1998. Storm-driven variability of the beach- nearshore profile at Duck, North Carolina, USA, 1981 - 1991. Marine Geology, 148, 163 - 177.

Marsh, S.W., Nicholls, R.J., Kroon, A., and Hoekstra, P., 1988. Assessment of depth of closure on a nourished beach: Terschelling, The Netherlands. These proceedings.

Nanninga, M., 1985. The accuracy of echo sounding - description in a mathematical model. Masters Thesis. Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ.

Nicholls, R.J., Birkemeier, W.A., and Hallermeier, R.J., 1996. Application of the depth of closure concept. Proc. 25th ICCE, Orlando (USA), ASCE, New York pp. 3874-3887.

Nicholls, R.J., and Birkemeier, W.A., 1997. Morphological and sediment budget controls on depth of closure at Duck, NC. Proc. Coastal Dynamics 1997, ASCE, New York. pp. 496 - 505.

Nicholls, R.J., Birkemeier, W.A., and Lee, G., 1998. Evaluation of depth of closure using data from Duck, NC, USA. Marine Geology, 148, pp. 179-201.

Roelvink, J. A., and Stive, M. J. F., 1990. Sand transport on the shoreface of the Holland coast. Proc. 22nd Coastal Engineering Conf., ASCE, New York. pp. 1909 - 1921.

Roelvink, J.A., Boutmy, A.E.G., and Stam, J-M, T., 1998. A simple method to predict long-term morphological changes using complex model results. These proceedings.

Roskam, A.P., 1988. Golfklimaten voor de Nederlandse kust. Rijkswaterstaat, Nota GWAO-88.046, 21pp. + figures.

Stive, M.J.F., Roelvink, J.A., and De Vriend, H.J., 1990. Large-scale coastal evolution concept. Proc. 22nd Coastal Engineering Conf., ASCE, New York. pp. 1962 - 1974.

Van de Meene, J.W.H., 1994. The shoreface connected ridges along the central Dutch coast; The Netherlands. PhD Thesis, Utrecht University, Department of Geography, The Netherlands. 222pp.

Wijnberg, K.M., 1995. Morphologic behaviour of a barred coast over a period of decades. PhD Thesis; Utrecht University, The Netherlands. 250pp.