CHAPTER 158

Evaluation of beach modelling techniques behind detached breakwaters

Philip Axe[1], Suzana Ilic[1] and Andrew Chadwick[2]

1 Abstract

This paper presents an evaluation of current design formulae for beach response to multiple breakwaters, comparing the predictions of the design guidelines with observations of beach response made during the large scale field experiment carried out at Elmer, on the UK south coast. The introduction describes typical shoreline response to breakwaters, the forcing mechanisms responsible and the characteristics of macro-tidal beaches. The remainder of the paper presents the empirical design tools, and the results of the evaluation.

2 Introduction

Detached breakwaters have been used for coastal protection throughout this century. Experience of the effects of such structures on macro-tidal beaches is limited however, and little information is available to design engineers on the response of coarse grained beaches to detached breakwaters. Salient and tombolo formation has been observed behind both natural and man-made coastal structures. Circulatory gyres in the lee of these structures, responsible for this planshape development, have long been observed (e.g. Sauvage *et al*, 1954). The forcing mechanisms responsible for these gyres have been identified as due to longshore currents set up by oblique breaking of diffracted waves, and also due to differences in set-up at the shoreline, due to longshore differences in wave height, again due to diffraction.

2.1 Shoreline response to single units

Shoreline response to single offshore breakwaters is dominated by the ratio of breakwater length to offshore distance. The influence of this ratio can be seen in the data collated in Hsu and Silvester's (1990) paper. This data is plotted in figure 1 as

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[1] Researchers, [2] Reader, School of Civil and Structural Engineering, University of Plymouth, PL4 8AA, United Kingdom

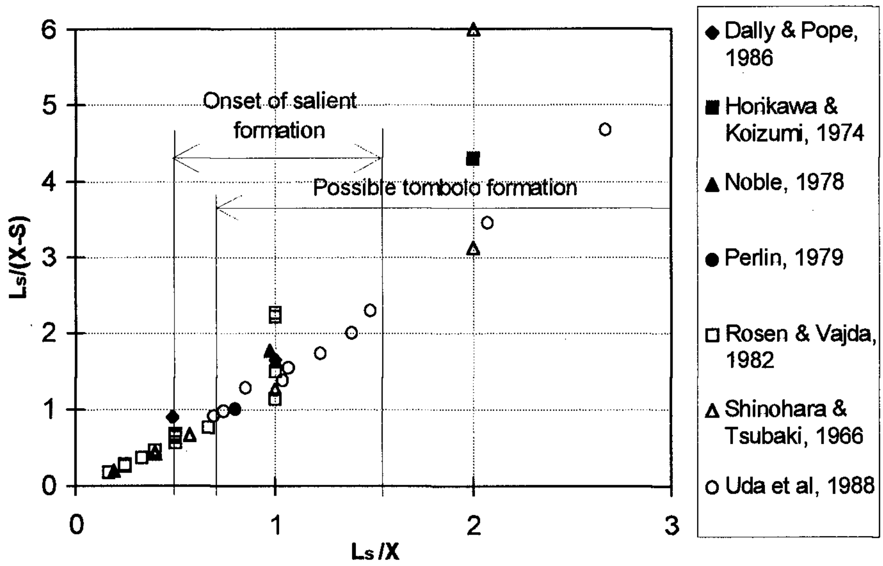

Figure 1. Ratio of breakwater length to breakwater-salient tip distance, plotted against breakwater length to offshore distance, collated by Hsu and Silvester, 1990

the ratio of breakwater length (L_s) to breakwater-salient tip distance (X-S), against the ratio of breakwater length to offshore distance (X). (A schematic diagram showing the meaning of the various dimensions is shown in the appendix. The data has been replotted in this way to illustrate clearly both the clarity of the relation, and also the spread of data, especially at higher values of L_s/X. This variability is not apparent in the original graph, where the data is fitted to a *1/x* type curve.). This data is obtained from a variety of prototype schemes, physical models and a set of numerical tests (Perlin, 1979).

The importance of the ratio of L_S/X has been observed by many researchers, and forms the basis of several empirical prediction schemes. The exact shoreline response to a particular value of L_S/X is not definable, but in the literature, the onset of tombolo formation has been observed for values of L_S/X between 0.67 and 2.5, while salients begin to form for values between 0.5 and 1.5. No shoreline response is observed for values of L_S/X less than 0.5. Chasten *et al* (1993) presents a good review of the literature.

The uncertainty in predictions of shoreline response to single units is due to the combined influence of other factors, such as the size and availability of sediment, structural properties (such as the porosity- determined by armour and core sizes, and packing and freeboard, which control wave transmission) of the breakwater, and wave conditions (such as the directional spread of the incident wave energy).

2.2 Multiple breakwaters

For multiple detached breakwaters, the task of predicting shoreline response is more complex. In addition to the parameters controlling beach response described previously, the breakwater gap width has a major effect on the final beach plan shape. The gap width controls the amount of energy reaching the shoreline and thus available to drive longshore currents. The relative gap width (that is, the ratio of the gap width to the incident wavelength) also controls the way in which incident waves are diffracted, which in turn affects the currents responsible for the beach planform development. Where the gap is large compared to the incident wavelength, wave diffraction is considered to occur at the breakwater tip, and the breakwater may be considered to behave as an individual structure. Where the gap width is small, the diffraction appears to be from the centre of the gap, and the shoreline response to the two breakwaters can be considered to be governed by both breakwaters.

Previously, experience of detached breakwater design has been concentrated in micro- and meso-tidal regimes, such as Japan (see, for e.g., Seiji *et al*, 1987) the Italian Adriatic (Liberatore, 1992), the Spanish Mediterranean (Berenguer and Enriquez, 1988), or the Great Lakes (e.g. Pope and Rowen, 1983). The UK south coast is a strongly macro-tidal environment, and this has implications for detached breakwater design.

Current design guidance gives predictions of the still water shoreline position. In a macro-tidal regime, in order to maintain a suitable berm width under storm conditions, the design engineer is interested in knowing the high water shoreline position. Figure 2 highlights the problem, showing a 3D surface of a section of the Elmer frontage, with the shoreline positions at low water, mid tide and mean high water marked. It can be seen from this figure that at low tide, the breakwaters are above the water line, and only operate as the tide rises. The tidal rise increases the offshore distance of the breakwaters.

In addition to the varying geometry of the system, the changing water levels also affect the incoming waves. At lower tidal levels, waves are more likely to be depth limited, and the breakwaters lie within the surf zone. This condition is favours tombolo formation (Gourlay, 1987). At high water, the breakwater are well offshore, and waves break straight onto the beach. The wavelength of an incoming wave is reduced at low water, which changes the relative gap width, which in turn is responsible for controlling whether the breakwater acts as a single unit, or as part of an array. The question that we want to answer is this:

'Is an equilibrium beach planform reached for every tidal level (in which case it would be simple to map the 3D morphology of the beach), or does the beach only come into equilibrium at the high and low water stands (where the rate of change in water depth is a minimum)?'

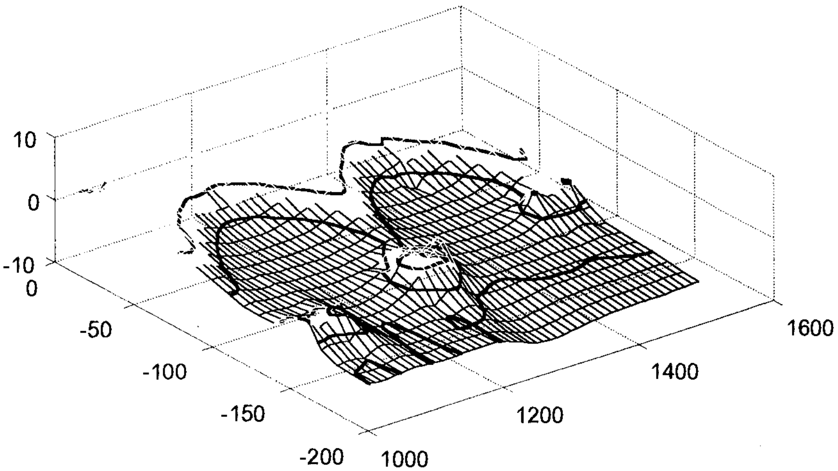

Figure 2 Positions of low water, mid tide and high water shorelines (solid black lines) at Elmer. All dimensions are in metres

2.3 Field Study

A field experiment, to study the shoreline response to a new set of breakwaters was devised and carried out at Elmer, between 1993 and 1995. Elmer lies on the UK south coast, 15 km from the western boundary of the Selsey Bill - Thames estuary coastal cell. The predominant drift direction along this coast is from west to east. The study site is the most seaward protrusion along an otherwise straight stretch of coastline, and has thus behaved as a headland area. In the winter of 1989, severe storms led to flooding of the residential hinterland. Works were planned, and constructed between 1992 and '93. These consisted of a 239,000 m^3 beach fill along 2 km of frontage, stabilised by eight shore-parallel offshore breakwaters and a terminal rock groyne (described in Holland and Coughlan, 1993). A plan of the scheme is shown in figure 3.

The field work program provided wave data recorded simultaneously at the shoreline and offshore. Data was processed using common spectral and directional analysis routines. Beach surveys were taken concurrently with the wave data collection. Data was collected for at least one year, to avoid seasonal bias.

One wave recorder (a pressure transducer array described in Bird, 1993) was deployed 650 metres offshore, towards the western end of the scheme. This provided the incident wave conditions. At the shoreline, the Inshore Wave Climate Monitor (IWCM- described in Chadwick, Borges, Pope and Ilic, 1995) was deployed to provide directional wave conditions after the waves had been diffracted through the gap between breakwaters three and four.

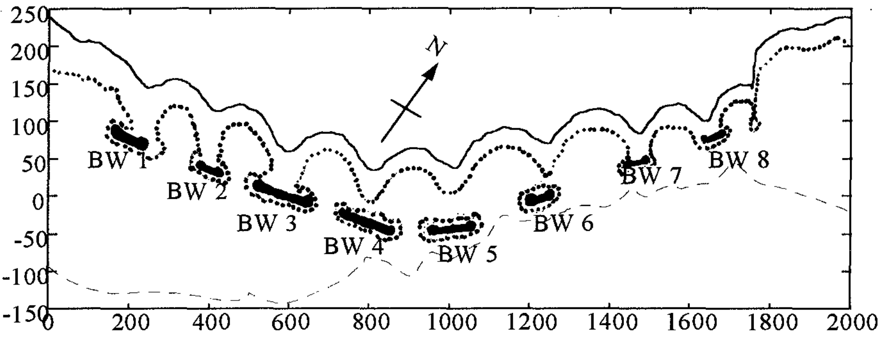

Figure 3. Elmer frontage, showing numbering scheme for breakwaters, and levels of highest (solid line) spring, mid (dotted line) and lowest spring (dashed line) tides

Photogrammetric surveys of the beach were commissioned in collaboration with the local coastal protection authority. Aerial surveys provided overlapping colour prints, at a contact scale of 1:3000, of the coastline up to 2 kilometres east of the scheme, and 1 kilometre west. Profile data was provided along profile lines set in discussion with the local coastal protection authority. This gave 65 cross shore profile lines, and 4 longshore lines. Within the scheme, profile line spacing was 30 metres, with the exception of the instrumented area, where a line spacing of 10 metres was provided. Beyond the limits of the scheme, line spacing was 50 metres. The first survey was produced on completion of the scheme (September '93), and then on the following dates: 2 February '94; 29 May '94; 16 September '94; 29 January '95 and 16 May '95. Below the low tide limit, bathymetric data was obtained by an echo sounder survey. A summary of data collected is presented in table 1, and monthly averages of wave conditions are shown in figure 4.

Parameter measured	Method	Start date	End date	Data availability
Directional wave conditions (offshore)	Sub-surface pressure transducers	23 September 1993	14 January 1995	2776
Directional wave conditions (inshore)	Direct measurement by resistance staffs	5 October 1993	13 December 1994	1550
Wave induced currents	Electromagnetic current meters, float tracking	18 April 1994	24 April 1994	24
Beach profiles	Aerial survey	September 1993	May 1995	6 surveys
Beach samples	Direct sampling	April 1994	June 1995	22 samples

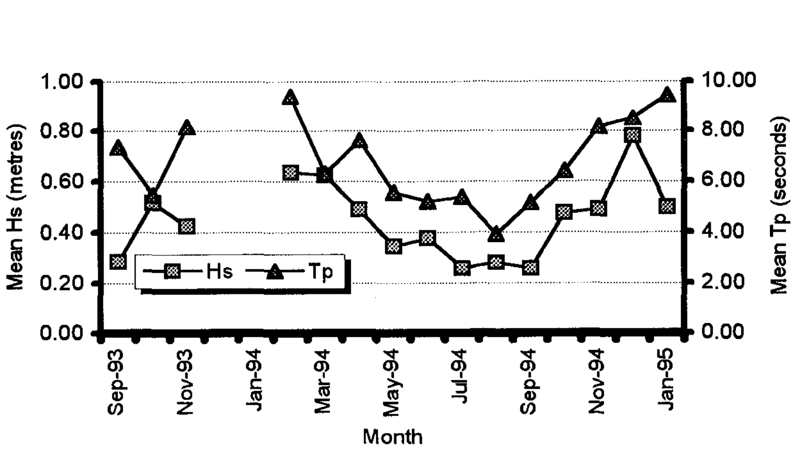

Figure 4. Monthly averaged wave conditions (offshore)

1 Evaluation of empirical models

Four models were selected for evaluation. These were : Pope and Dean (1986); Suh and Dalrymple (1987); Ahrens and Cox (1990); and McCormick (1993). Of these, Suh and Dalrymple and McCormick's models provide values of salient length (Suh and Dalrymple) or of shoreline position (McCormick), whereas the Pope and Dean, and Ahrens and Cox models both describe the beach response in general terms.

The Suh and Dalrymple model is based on a set of physical model tests carried out in a spiral wave basin, and on prototype and model tests described in the literature. The equation presented to fit this data is:

$$S^{*} = 14.8\left(\frac{G_B^{*}}{L_B^{*}}\right)\exp\left[-2.83\left(\frac{G_B^{*}}{L_B^{*}}\right)^{\frac{1}{2}}\right] \qquad \text{Equation 1}$$

where X_s is the salient length, G_B is the gap width, and L_B is the breakwater length. Characters marked with an asterisk represent values non-dimensionalized with respect to the offshore distance of the structure.

The McCormick (1993) model is based on the observation that bays formed behind detached breakwaters tend to be ellipsoid. This observation was based on aerial photographs, and on selected physical model data of Shinohara and Tsubaki (1966) and of Rosen and Vajda (1982). Validation for the model was carried out on four breakwaters within the 'Bay Ridge' prototype scheme in Chesapeake Bay. This model is more complex than the others studied. It is still based primarily on the ratio of offshore distance to breakwater length, but also includes the effects of wave steepness, direction and beach slope. These values are used to predict the size and locations of the ellipses that define the shoreline position. For the purposes of this evaluation, the predictions of salient length were extracted from this information. The reader is recommended to read McCormick's original paper for details of the application of this model.

Pope and Dean (1986) proposed a system of classifying the effect of breakwater schemes in terms of their shoreline response. Beach response was divided into five bands, ranging from '*no sinuosity*' through '*subdued salients*', '*well developed salients*', and '*periodic tombolos*' to '*permanent tombolos*'. The classification is based on the degree of protection afforded to a coastline (in terms of the ratio of breakwater length to gap length) plotted against the ratio of offshore distance to water depth at the structure. Preliminary results of a validation of this method were presented for low to moderate wave climates.

Ahrens and Cox (1990) followed the classification scheme proposed by Pope and Dean, defining a beach response index I_s. The index is defined below, in equation 2.

$$I_s = e^{\left(1.72 - 0.41 \frac{L_S}{X}\right)} \qquad \text{Equation 2}$$

Values of I_s less than 1 predict permanent tombolo formation, while values greater than 5 predict no sinuosity. The method is based purely on the breakwater length and offshore distance, and therefore ignores any effects of variable gap width.

To apply these models to the Elmer site, the profile data and construction plans were analysed to provide information on the scheme geometry. Because of the interest in the ability of these schemes to predict beach response at varying tidal levels, measured salient lengths, offshore distances, beach slopes and water depths were extracted at 0.3 metre intervals, from the mid tide level up to mean high water springs (2.4 metres higher). This information was then used to drive the models, and the predictions were compared with the observed findings. Offshore distances of the breakwaters are presented in Table 2, while measured salient lengths are presented in Table 3.

Water level (over mean water level)	Break water 1	Break water 2	Break water 3	Break water 4	Break water 5	Break water 6	Break water 7	Break water 8
0	50.6	48.7	0	40.9	54.5	44.3	25.5	10.4
0.3	68.2	65.3	3.9	42.9	57.1	47.3	29.1	13.5
0.6	72.1	68.2	51.3	45.8	59.7	50.4	32.2	16.7
0.9	73.1	72.1	54.5	48.7	62.3	53.4	34.3	19.8
1.2	76	74	57.1	52.6	64.9	56.5	36.4	21.9
1.5	77.9	77.9	59.7	55.5	67.5	59.5	38.4	24
1.8	80.8	80.8	62.3	58.4	70.1	62.6	41	27.1
2.1	83.8	82.8	66.2	60.4	72.7	65.6	43.6	29.2
2.4	85.7	85.7	68.2	66.2	75.3	68.7	46.2	32.3

Table 2. Breakwater-shoreline distances at various tidal levels

Water level (over mean water level)	Break water 1	Break water 2	Break water 3	Break water 4	Break water 5	Break water 6	Break water 7	Break water 8
0	51	49	0	41	30	44	26	10
0.3	68	65	4	43	21	15	29	14
0.6	72	64	51	46	18	9	32	17
0.9	54	35	55	16	16	5	34	20
1.2	35	27	38	14	14	1	34	19
1.5	27	23	28	5	12	-1	34	19
1.8	22	19	23	2	8	-2	35	20
2.1	22	11	21	0	8	-5	32	18
2.4	20	10	18	0	6	-7	31	17

Table 3. Observed salient lengths at various tidal levels

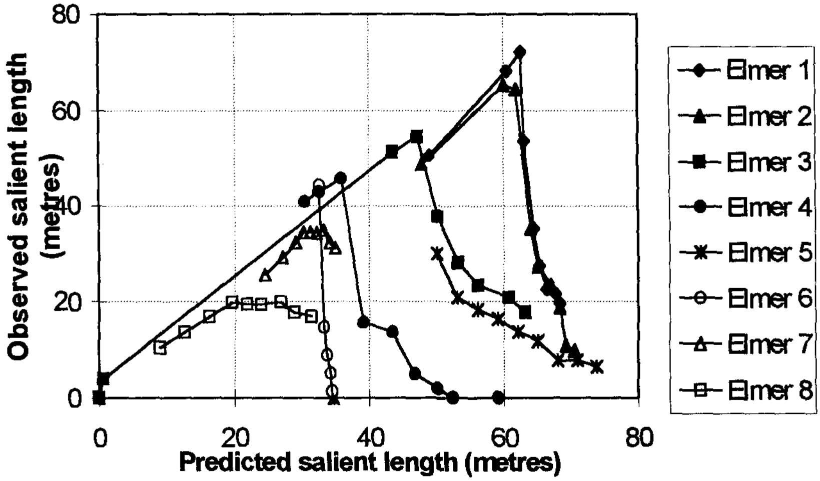

Figure 5. Comparison of observed and predicted salient lengths, based on Suh and Dalrymple, 1987

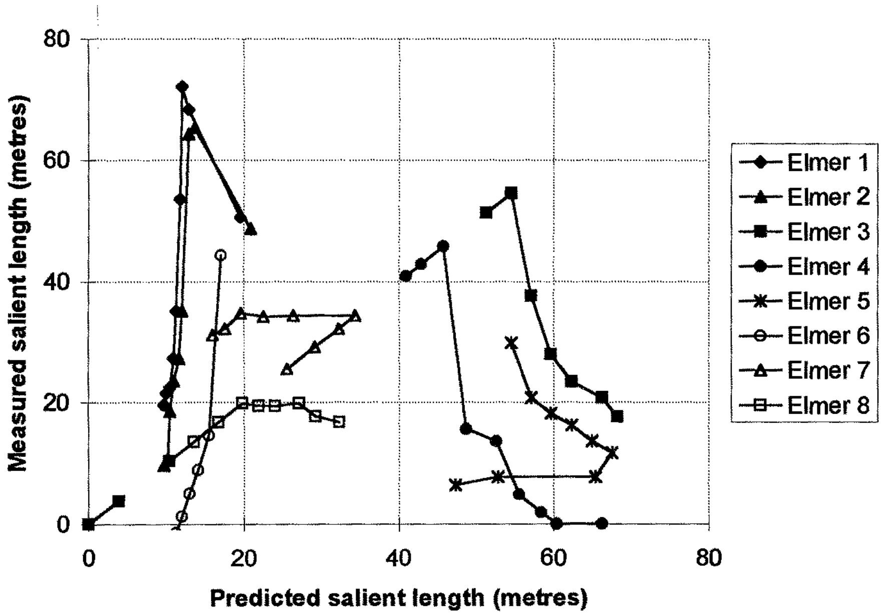

Figure 6. Comparison of observed and predicted salient lengths, using McCormick, 1993

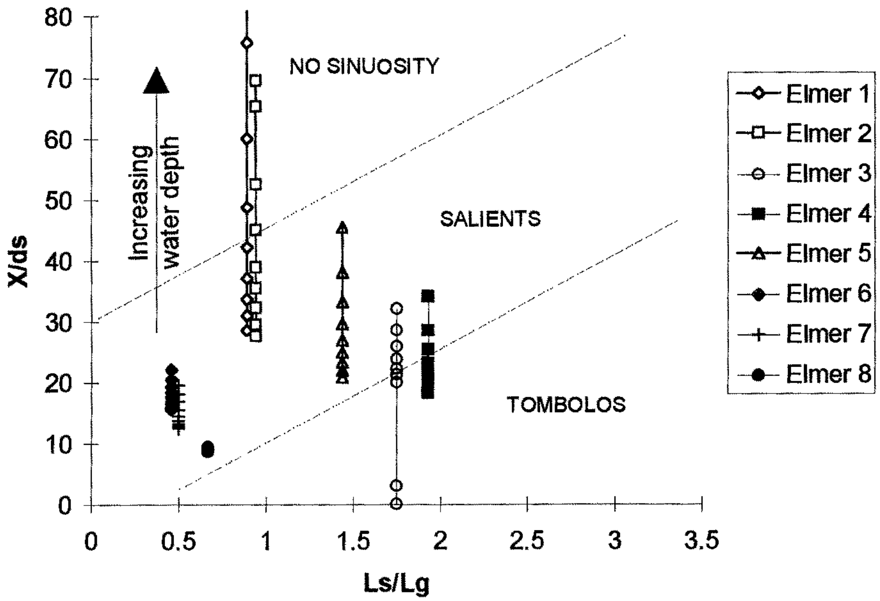

Figure 7. Elmer breakwaters plotted according to the classification scheme of Pope and Dean (1986)

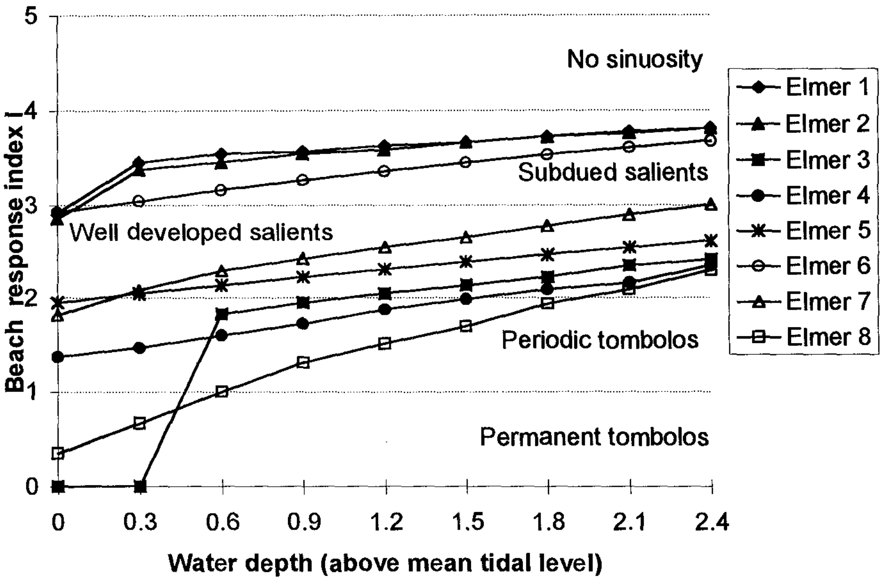

Figure 8. Variation in breakwater index with tidal level, according to the classification scheme of Ahrens and Cox (1990)

4 Results

The model predictions from Suh and Dalrymple (1987) shown in figure 5, show excellent agreement between observed and predicted salient lengths at the lower levels- when tombolos occur. As the tide rises, this model predicts steadily *increasing* salient lengths. This is counter to the observed salient behaviour, but in line with the observations reported in Chasten *et al* (1993). The response predicted by McCormick's model (shown in figure 6) differs from this. Similar tombolo formation was predicted at the lower tidal levels. Salient length was predicted to decrease behind breakwaters 1,2,6 and 7, and predicted to increase behind breakwaters 3,4 and 8. In the case of breakwaters 1 and 2, this decrease in salient length improved the quality of the predictions, but for the other breakwaters, the predictions worsened at the higher tidal levels.

Figure 7 shows the predictions according to Pope and Dean's classification. Tombolo formation is only predicted to occur behind breakwaters 3 and 4, although the prediction of the limit between salient and tombolo for breakwater 3 is perfect. The limited shoreline response behind breakwaters 1 and 2 at high tide is also represented well, but tombolo formation at low water is not predicted. Figure 8 shows the effect of varying water depth on Ahrens and Cox's beach response index. Tombolo formation is predicted at mid tide behind breakwater 3,4,5,7 and 8. A tombolo does not form behind breakwater 5 however, and the tombolos behind breakwaters 1 and 2 were not predicted to occur. As the water depth is increased, the transition from tombolo to salient is reasonably well described.

5 Discussion

From these results, it appears that the methods of Suh & Dalrymple, and of McCormick, work very well for describing tombolo formation, but do not appear to be as reliable when modelling salient formation. This may be due to a tendency to over predict salient lengths, which is a characteristic that would be masked when comparing these models with field tombolos. This tendency has been observed previously and reported in Chasten *et al* (1993). As a counter to this however, both models described the lower salient and tombolo formation behind breakwater 4.
The Suh and Dalrymple model was developed from physical model tests and prototype data where the gap widths between breakwaters was constant, and the beach response averaged across a scheme was evaluated. Where the gap widths are variable, as at Elmer, and individual salient lengths are required, the limits of applicability of this model may have been exceeded. Additionally, the study site is characterised by the bimodal nature of the beach. In the updrift west of the scheme, the tombolos are formed of sand, while the upper beach is gravel. In the (downdrift) east of the scheme, where the gap widths are wider, the tombolos are predominantly gravel. The formation of tombolos from finer material to the remainder of the beach leads to a difference in beach slope in the bays and on the tombolos. This in turn affects the rate at which parameters (non-dimensionalized against offshore distance) vary with depth. In the east of the scheme, this problem is less pronounced, due to the more uniform nature of the beach.

The more general predictors, of Pope and Dean, and Ahrens and Cox, were more successful in predicting beach response- due in part to the fact that as they only give general descriptions of a likely response. To illustrate this, it is clear that in figure 7, tombolos were no predicted to occur behind breakwaters 7 or 8. The observed response, shown in figure 3, is that tombolos formed. The response predicted by this method does however lie close to the limit of salient tombolo formation presented by Pope and Dean. Thus the predictions are reasonable. The prediction of the response to 3 and 4 was excellent. The method failed in the predictions of 1 and 2. As mentioned previously, the net drift direction at Elmer was from west to east, and this has led to an increased accumulation of material behind the first two breakwaters, that has not (yet?) been passed through the system. It may be supposed therefore that the Pope and Dean predictions are best used where longshore transport into a system is not significant, such as in a pocket bay, or indeed in the middle of a scheme of breakwaters. This failure to predict the beach response to breakwaters 1 and 2 also occurs with Ahrens and Cox's technique, although this method does succeed in predicting the tombolos behind breakwater 8 (and less well) breakwater 7.

6 Conclusions

From the comparison of the predicted and observed salient lengths during this exercise, three of the predictive schemes (Ahrens and Cox, McCormick, and Pope and Dean) were unable to predict the behaviour of the updrift breakwaters. This suggests that these techniques are not suitable for use where there is significant longshore transport into a scheme, which restrict their use to the design of pocket beaches, or to the central portions of multiple breakwater schemes, where net longshore transport is expected to be low. The robustness of the simplest technique (Ahrens and Cox) is surprising, suggesting that even in multiple breakwater schemes, the ratio of breakwater length to offshore distance is still paramount in determining shoreline response. This would seem to be contrary to other research (such as, for example, Hanson, Kraus and Nakashima, 1989), which suggested that wave transmission, for example, was an important parameter in determining shoreline response. The findings in this work are most likely to be a result of this evaluation being well within the range of applicability of the Ahrens and Cox method.

The inability of these methods to predict shoreline positions behind detached breakwaters does make them of less use to design engineers. To improve our design capability, physically based numerical process models, validated against field measurements, are needed before we can confidently develop 'rules of thumb' to simplify design.

7 Acknowledgements

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9 Notation

L_S	Breakwater length (metres)
X	Offshore distance of breakwater (metres)
S	Salient length (metres)
L_G	Gap width
ds	Water depth at seaward side of breakwater
λ	Water wavelength
*	Non-dimensionalised with respect to X

10 Appendix

Schematic diagram explaining notation