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## Guidance for outline design of nearshore detached breakwaters on sandy macro-tidal coasts

Project: SC060026/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

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# Executive summary

This report provides guidance for the outline design of a nearshore detached breakwater scheme for beach erosion control on a sandy coast. The design guidance includes the effect of tides, width of the surf zone, breakwater crest level and other geometrical parameters of the detached breakwater scheme. This guidance only provides advice on determining the parameters required to develop a preliminary geometrical layout.

The guidance is intended to be applied by experienced coastal engineers and requires skill and expertise to interpret the input and output parameters.

The design guidance is based on coastal area morphological modelling results for several generic test cases (30 test cases in total) under a variety of wave and tidal forcing conditions. Further details about the modelling results are provided in the accompanying science report (Environment Agency 2009).

A step-by-step block flow chart supported by two worked examples is provided.

It is envisaged that coastal practitioners will use this guidance at the option appraisal stage to help evaluate the effect of nearshore breakwaters on the shoreline and to assist in decision making regarding suitable approaches to managing beach levels. If a breakwater scheme option is selected at this stage, detailed analyses should then be carried out for the particular site to develop a preliminary design and to confirm the breakwater layout before carrying out a detailed design. A brief description of the tools available for detailed analysis of the impact of nearshore breakwaters on coasts is included.

# Acknowledgements

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We would also like to thank all members of the parallel LEACOAST2 research consortium, funded by the EPSRC, for the constructive discussions over the course of the project. The extensive field and numerical modelling work carried out by the research consortium to study the nearshore breakwater scheme at Sea Palling, Norfolk, UK, provided a good foundation for the work carried out in this study.

Lastly, we would also like to thank the following for their valuable contributions to the project: Suresh Surendran, Stefan Laeger, Ben Hamer, Jonathan Rogers and Adam Davidson.

# Abbreviations

| | |
|---|---|
| Defra | Department for Environment, Food and Rural Affairs |
| HW | High water |
| MHWS | Mean high water spring |
| MLWS | Mean low water spring |
| MSL | Mean sea level |

# Contents

# 1 Introduction

## 1.1 Need for guidance

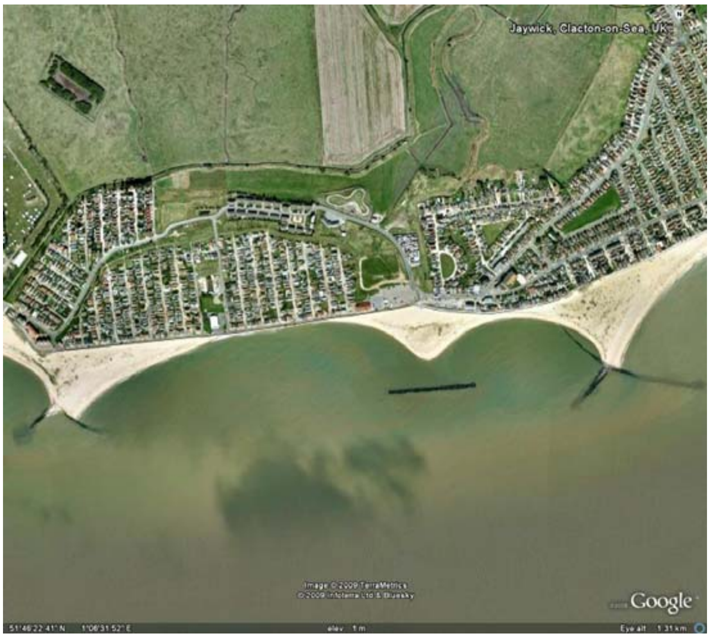
Nearshore detached breakwaters are often considered an option for beach erosion control as part of coastal defence schemes. Detached breakwaters have been used extensively in Japan, the US, Singapore and the Mediterranean. Their use in the UK is more recent (CIRIA 1996). Examples of nearshore detached breakwaters around UK coasts are shown in Figure 1.1 and Figure 1.2.

Sea Palling, Norfolk

Elmer, West Sussex

**Figure 1.1 Example breakwater schemes around UK coasts (1).**


Sidmouth, Devon




Jaywick, Essex

**Figure 1.2 Example breakwater schemes around UK coasts (2).**

Rogers *et al.* (2006) carried out a review of existing design guidance for determining the geometrical layout of breakwater schemes and concluded that the existing guidance is largely based on empirical data from micro-tidal coasts (tidal range <2m). Thus, the existing guidance may not be applicable to meso-tidal (tidal range between 2m and 4m) and macro-tidal (tidal range >4m) coasts. Furthermore, O'Connor *et al.* (1995) showed that existing design guidelines can often be contradictory even for micro-tidal coasts. This is shown by the inability of some engineering criteria to predict correctly the formation of salients and tombolos in the lee of such structures.

More than 75 per cent of the UK coastline can be classified as meso- or macro-tidal (with spring tidal range >2m; see co-tidal chart 5058 from the UK Hydrographic Office), which makes it important that guidance on the outline design of such structures in meso- and macro-tidal coasts be developed.

In order to bridge this gap, the joint Environment Agency/Department for Environment, Food and Rural Affairs Flood and Coastal Erosion Risk Management programme commissioned a research study to help improve practical design guidance. This guidance document and the companion science report (Environment Agency 2010) are the results of that study.

## 1.2 Users of this report

This report is aimed at providing the coastal practitioner with guidance on selecting the geometrical layout of detached breakwater schemes for beach erosion control. It is envisaged that coastal practitioners will use this guidance at the option appraisal stage to help them evaluate the effect of nearshore breakwaters on the shoreline. Note that if a breakwater scheme option is selected at this stage, detailed analyses should be carried out for the particular site before carrying out the detailed design. Techniques for detailed analysis are also discussed briefly in this report.

## 1.3 This report

This report presents a summary of the recommendations for outline design guidance based on the scientific results of the research study. The remainder of this report is organised as follows.

**Chapter 2** contains a summary of the effects of nearshore detached breakwaters on beach response.

**Chapter 3** contains step-by-step guidance for outline design.

**Chapter 4** contains two worked examples.

**Chapter 5** contains a discussion of the tools available for site-specific detailed analysis.

# 2 Effect of breakwaters on beach response

## 2.1 Effect of detached breakwaters

The effect of a detached breakwater is to reduce the incident wave energy on a section of the coast in its lee. This reduction of wave energy in the lee of a breakwater scheme induces complex flow circulation patterns due to gradients in wave set-up, wave-driven longshore flow and tidal flows, resulting in complex sediment transport patterns. In a meso- or macro-tidal environment, the littoral zone[1] is continually changing as the water level changes with the tide. Furthermore, the tidal currents also interact with the wave-driven currents, leading to more complex flow and sediment transport patterns. These complex sediment transport patterns result in morphological changes in the vicinity of the breakwater. These changes include: a) sediment deposition in the lee of the breakwater; b) erosion in the breakwater bays; and c) scour near the breakwater heads.

Thus understanding the likely incident wave and water level conditions, how the breakwater influences the incident wave energy distribution and tidal flows on the beach, and the beach's response to the new conditions are the three key elements for selecting an appropriate geometrical layout of a nearshore detached breakwater scheme.

The first step in designing a nearshore detached breakwater scheme, or other beach control option, is often to consider what change is required to the existing shoreline. At option evaluation stage, the shoreline response in the lee of a breakwater is typically classified as shown in Table 2.1.

**Table 2.1 Description of accreted shorelines in the lee of detached breakwater.**

| Shoreline response | Description | Example[1] |
|---|---|---|
| Limited response | Limited changes in the shoreline planform due to sediment deposition leeward of breakwater. | Sidmouth, Devon |
| Salient | Noticeable bulge in the shoreline planform due to sediment deposition leeward of breakwater. | Elmer, West Sussex; Jaywick, Essex |
| Tidal tombolo | Tombolo at low water, but salient at higher tide levels. | Sea Palling, Norfolk |
| Tombolo | Shoreline that has connected to breakwater due to sediment deposition leeward of breakwater. | Sea Palling, Norfolk |

[1]See photographs of example breakwater schemes in Figure 1.1 and Figure 1.2.

[1] The littoral zone is the zone between the shoreline and a location offshore where significant longshore sediment transport takes place.

The morphological changes described above are controlled by the incident wave and water level conditions, the sediment characteristics and the geometrical layout of the breakwater scheme. The key variables specified in an outline design are illustrated in Figure 2.1.

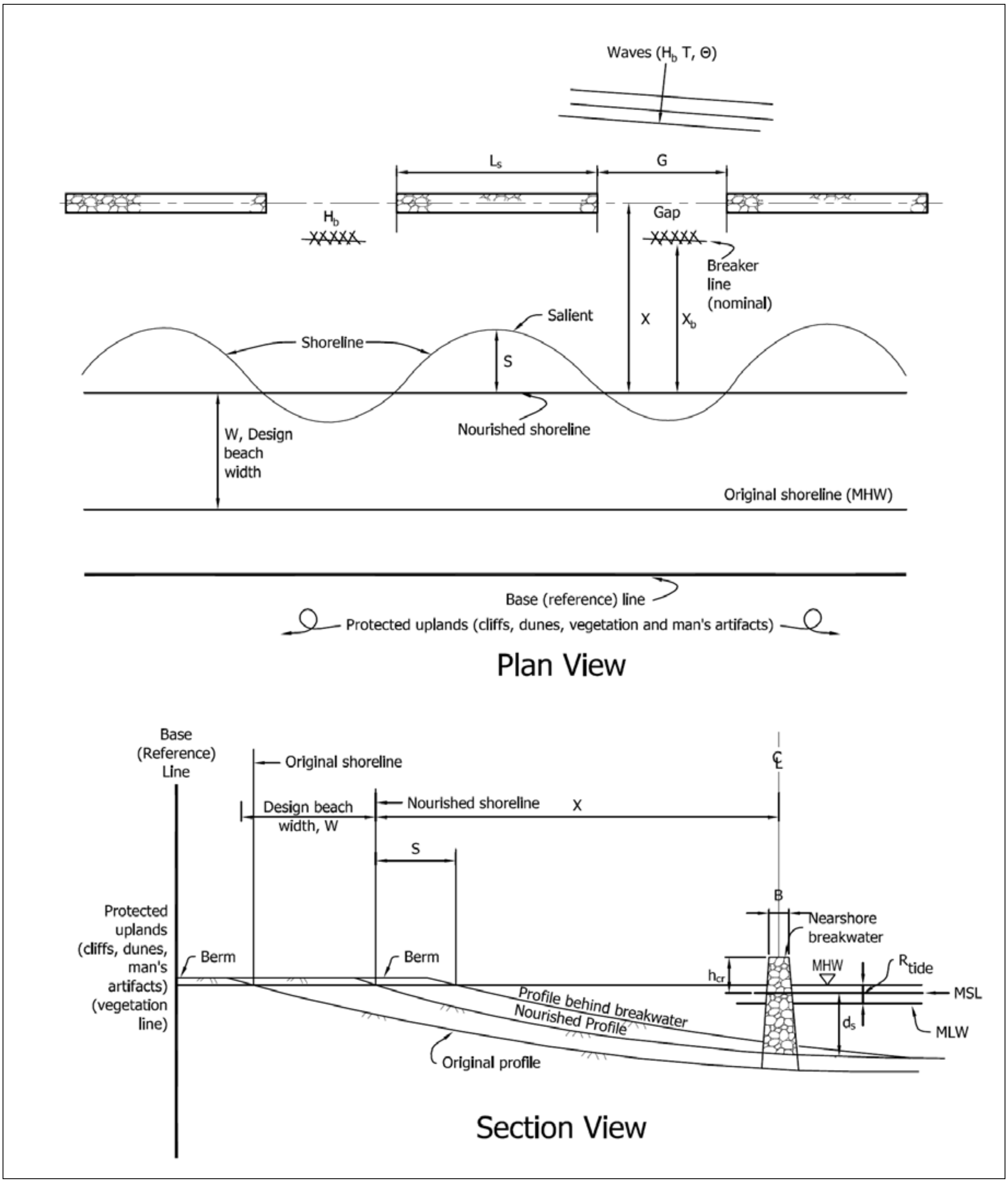



**Figure 2.1 Definitions of key variables for nearshore breakwater scheme (adapted from USACE 2003).**

## 2.2 Dimensionless parameters

The dimensionless analysis carried out in this study showed that the beach response in the vicinity of nearshore breakwaters on macro-tidal sites is a function of the following parameters:

- $L_s/X$ is a measure of the breakwater blocking efficiency.
- $X/X_b$ is the percentage of littoral drift affected by breakwaters (a measure of the relative location of the breakwaters in the surf zone).
- $G/L_0$ is a measure of the wave penetration through gaps.
- $B/L_0$ is a measure of the wave energy dissipation distance over the breakwater crest.
- $d_{cr}/H_b$ is a measure of wave energy dissipation rate over the breakwaters[2].
- $R_{tide}/H_b$ is a measure of the effect of tide range on the surf zone.
- $T_{tide}\sqrt{g/L_0}$ is the tidal period relative to the characteristic wave period.
- $U_{tide}/\sqrt{gH_b}$ is a measure of the effects of tidal current relative to wave-induced current.
- $\varphi$ is a measure of the type of tidal regime.
- $H_b/D_{50}$ is a measure of the sediment mobility.
- $S_g$ [=sqrt($D_{84}/D_{16}$)] is a measure of the sediment grading.
- $\theta$ is a measure of the mean wave direction.

The beach response is typically characterised in terms of accretion in the lee of the breakwater (see Table 2.1) and erosion at the shoreline between the breakwater gaps.

Not all the above parameters will be important in certain situations, leading to a reduced number of parameters for describing the morphological response. Example simplifications are presented in Table 2.2 for fixed beach sediment parameters and tidal period (not considering $H_b/D_{50}$, $S_g$ and $T_{tide}\sqrt{g/L_0}$ ).

[2] $d_{cr}$ is the depth of water at the breakwater crest during high water. It is related to the breakwater crest elevation, $h_{cr}$, shown in Figure 2.1. $d_{cr}$ is used as an alternative parameter to $h_{cr}$ in the dimensional analysis, as it is considered to be a more meaningful measure of wave transmission.

**Table 2.2 Dimensionless parameters for morphological response behind shore parallel breakwaters.**

| PARAMETER | DESCRIPTION |
|---|---|
| Multiple breakwaters, no tides, submerged | $\Pi_A = f(\frac{L_S}{X}, \frac{X}{X_b}, \frac{G}{L_0}, \frac{B}{L_0}, \frac{d_{cr}}{H_b}, \theta)$ |
| Multiple breakwaters, no tides, emergent | $\Pi_A = f(\frac{L_S}{X}, \frac{X}{X_b}, \frac{G}{L_0}, \theta)$ |
| Single breakwater, no tides, submerged | $\Pi_A = f(\frac{L_S}{X}, \frac{X}{X_b}, \frac{B}{L_0}, \frac{d_c}{H_b}, \theta)$ |
| Single breakwater, no tides, emergent | $\Pi_A = f(\frac{L_S}{X}, \frac{X}{X_b}, \theta)$ |
| Single breakwater, no tides, emergent, constant wave direction | $\Pi_A = f(\frac{L_S}{X}, \frac{X}{X_b})$ |

## 2.3 Modelling studies to support guidance

Numerical (computer-based) modelling studies were undertaken for a number of test cases to provide the key data that feeds into this guidance. Two advanced numerical coastal area morphological models (PISCES and MIKE 21 CAMS) were used to simulate 30 combinations of breakwater layouts, wave conditions and tidal conditions. A detailed discussion of the model setup and results can be found in the companion science report (Environment Agency 2010).

Coastal area morphological models have developed significantly since the early 1990s and recent applications have shown that nearshore morphological prediction can now be undertaken successfully. Recent successful applications of coastal area morphological models, including for various breakwater schemes, can be found in Nicholson *et al.* (1997), Damgaard *et al.* (2003), Sutherland *et al.* (2004), Johnson *et al.* (2005), Van Rijn *et al.* (2005), and Zyserman *et al.* (2005).

The results from the 30 simulations were used to derive indicative trends on the effect of detached breakwater schemes on beach response. These trends are summarised in the sections below and form the basis of the new method for outline design of detached breakwater schemes presented in Chapter 3.

## 2.4 Non-tidal (or micro-tidal) beaches

Further investigation of the effect of breakwaters in non-tidal cases was carried out because existing design curves mainly consider the effect of $L_s/X$ on beach response. This is not completely correct, as the dimensionless analysis shows that the beach response is dependent on both $L_s/X$ and $X/X_b$ for non-tidal cases (when the breakwater cross-section and gap width between the emergent breakwaters are fixed).

Using the numerical model results from this study together with laboratory experiments compiled by Suh and Dalrymple (1987), the following trends were identified (see also Figure 2.2):

- For a given breakwater location in the surf zone ($X/X_b$), the dimensionless salient length (S/X) increases as the dimensionless breakwater length ($L_S/X$) increases.
- For a given $L_S/X$, the dimensionless salient length (S/X) increases for low values of $X/X_b$ and thereafter decreases, as should be expected for breakwaters located far away from the surf zone.
- Depending on the relative location of the breakwater in the surf zone, tombolo formation can occur for $L_S/X > 0.8$. The limiting conditions for tombolo formation are postulated as:

$$
\begin{aligned}
&L_S / X > 2.8 - 1.6\left(X / X_b\right) && X / X_b \le 1.25 \\
&L_S / X > -10.2 + 8.8\left(X / X_b\right) && 1.25 < X / X_b \le 2
\end{aligned}
\qquad (2.1)
$$

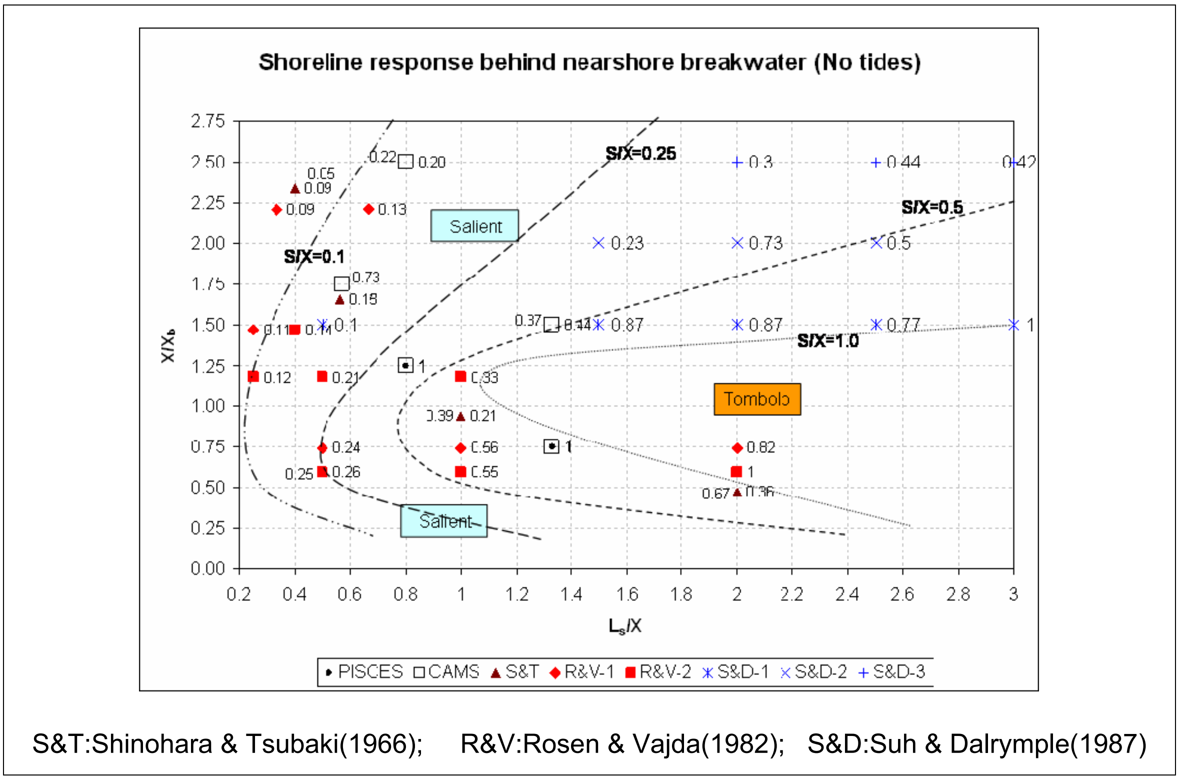



**Figure 2.2 Non-tidal cases from the numerical simulations and laboratory data from Suh and Dalrymple (1987).**
Notes: Labels on the plot are the dimensionless salient length (S/X).

# 2.5 Meso- and macro-tidal beaches

## 2.5.1 Effect of the type and range of tidal wave

The effect of the tidal range on the salient in the lee of the breakwater is illustrated in Figure 2.3. Both models show a decrease in the salient length with increasing tidal range. The relative salient lengths (S/X) reduce as the tidal range increases for shore normal waves. However, for large values, $L_s/X$ (> 1.3), the influence of tidal range is smaller if the breakwater is emergent through the tidal cycle.

However, for a given tidal range, the models show different responses to a change in geometry (changing $L_s/X$). The PISCES model results suggest that the dimensionless salient extent is practically unchanged for $L_s/X$ >0.8, while the MIKE 21 CAMS results show an increase in the relative salient length with increasing $L_s/X$. These differences are due to differences in the representation of certain physical processes in the models, and are further discussed in the science report (Environment Agency 2010).

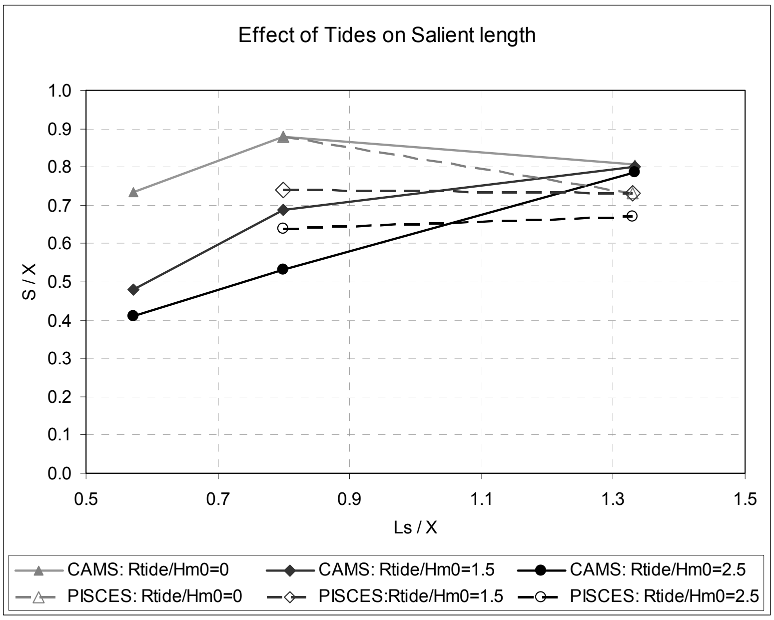



**Figure 2.3 Effect of breakwater length for different dimensionless tidal ranges ($R_{tide}$/Hm0; standing tides).**

The numerical simulations also show the following effects, depending on the tidal type.

- The base of the salient is wider in the tidal cases than in the non-tidal case.
- Progressive tides (where maximum current speed occurs near high water) result in deflection of the nearshore bathymetry in the direction of high water flow. Thus, the peak of the salient is deflected slightly downdrift compared to the case with standing tides.
- For the same tidal range, the salient length is slightly increased for standing tides (where maximum current speed occurs near mean sea level) compared with progressive tides.

### 2.5.2 Effect of oblique wave incidence

For oblique wave cases, sediment accumulation in the lee of the up-drift breakwater is larger than at the down-drift breakwaters. Furthermore, oblique wave incidence results in deflection of the salient in the direction of littoral drift.

However, the two numerical models used in the study show conflicting trends in the variation of salient length with tidal range for oblique wave incidence. The reason for the conflicting trends is differences in the representation of certain physical processes in both models; this is further discussed in the science report (Environment Agency 2010).

Fortunately, the incident wave conditions at any given site typically consist of a range of wave directions. Furthermore, detached breakwaters are usually oriented to be parallel to the shore, which is typically at a small angle to the dominant wave direction. Thus, it is suggested that for practical use at option evaluation stage the indicative trend for shore-normal waves in the preceding section should be used.

### 2.5.3 Effect of breakwater crest level

The numerical model simulations show that the relative salient length reduces as the breakwater crest level is reduced (Figure 2.4). The effect is more pronounced in cases where the breakwater is relatively close to the shoreline ($L_s/X \geq 1.3$).

Furthermore, the beach levels are lower as the breakwater crest level is reduced. This result is consistent with the observations at Sea Palling on the Norfolk coast, which show that the salient lengths behind low crested breakwaters are significantly shorter and the beach levels are lower compared with the adjacent high crested breakwaters.

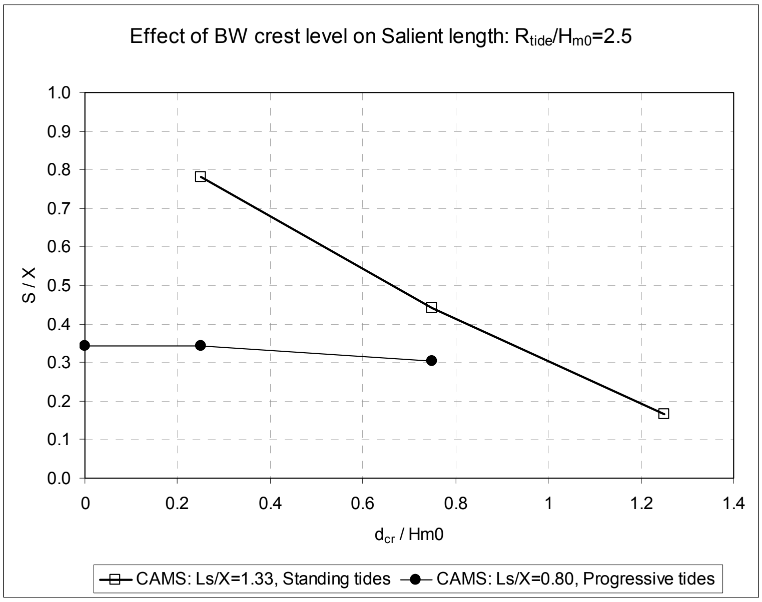



**Figure 2.4 Effect of breakwater crest level (relative submerged depth at high water, $d_{cr}/H_{m0}$) for different breakwater length ($R_{tide}$/Hm0=2.5).**

### 2.5.4 Erosion in the breakwater bays

For both normal and oblique wave incidence, erosion occurs in the breakwater bays and downdrift of the last breakwater in the scheme (for oblique wave incidence). The erosion is partly caused by longshore gradients in wave height (normal and oblique wave incidence) and partly by gradients in longshore transport (oblique wave incidence).

For normal wave incidence, some erosion will occur on both sides of the breakwater due to gradients in wave height.

The model results show that the seabed erosion across the nearshore profile in the breakwater bay generally reduces with increasing tidal range. There is more movement of the beach contours above mean sea level (MSL) and in particular more erosion above MSL with increasing tidal range. For oblique wave incidence, the area experiencing maximum shoreline erosion is shifted downdrift compared to normal wave incidence.

It was found that the simulated MSL shorelines for the bay with emerged breakwaters in tidal cases (and shore normal waves) agree reasonably well with the bay shoreline planforms predicted by the method of Silvester and Hsu (1997). This result should, however, be viewed with caution, since the breakwaters in the generic scheme layouts tested are largely independent of one another because of the large gap width[3].

#### 2.5.4.1 Shoreline planform using Silvester and Hsu (1997)

Silvester and Hsu (1997) proposed a method for determining the equilibrium shoreline planform in the lee of a single detached nearshore breakwater, based on the parabolic bay shape method. The key parameters are illustrated in Figure 2.5.

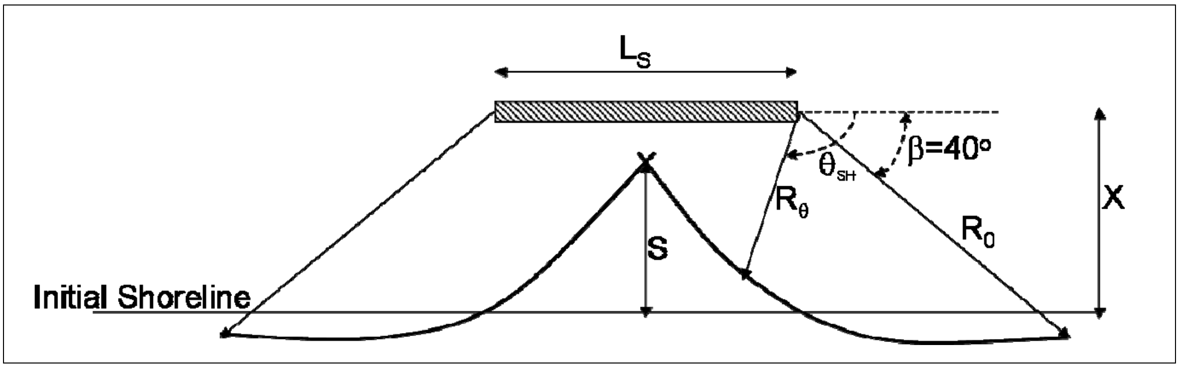



**Figure 2.5 Key beach and breakwater parameters in the Silvester and Hsu (1997) method.**

The parabolic bay shape method was originally developed for determining the equilibrium shoreline planform in bays. The relationship between the shoreline planform and the wave/breakwater parameters is given in equation 2.2 [$C_0$, $C_1$ and $C_2$ depend on the value of β (angle between the wave crest at the diffraction point and the control line, $R_0$ line)].

$$\frac{R_\theta}{R_0} = C_0 + C_1\left(\frac{\beta}{\theta_{SH}}\right) + C_2\left(\frac{\beta}{\theta_{SH}}\right)^2 \qquad (2.2)$$

Given values for $R_0$ and β, $C_0$, $C_1$ and $C_2$ can be determined and equation 2.2 can be used to calculate the shoreline planform (by calculating the values of $R_\theta$ for different values of $\theta_{SH}$). The reader is referred to Silvester and Hsu (1997) for further details.

For a single breakwater on an infinitely straight coast, Silvester and Hsu (1997) suggested using β=40° ($C_0$ = 0, $C_1$ = 1.32 and $C_2$ = -0.33) and equation 2.3 to

[3] The Silvester and Hsu method was applied separately for each individual breakwater and the results combined to obtain the shoreline planform in the presence of multiple breakwaters. This approach works well if the breakwaters are spaced apart such that they behave as independent breakwaters; however, it is not clear if the same approach can be used in cases where the wave conditions in the bay are significantly influenced by the gap width.

determine the length of the control line $R_0$. Thus, given $R_0$ and β, equation 2.2 can be used to calculate the shoreline planform (by calculating the values of $R_\theta$ for different $\theta_{SH}$ values). Table 2.3 gives the values of $R_\theta/R_0$ for various $\theta_{SH}$ values.

$$\frac{R_0}{L_S} = 0.1737 + \frac{1.683}{L_S / X} \tag{2.3}$$

For multiple breakwaters, the above method has been used to calculate the shoreline planforms (taken to be MSL) separately for each breakwater and combined together for the resulting shoreline planform.

**Table 2.3 Parabolic bay shape parameters for single breakwater (β=40°).**

| $\theta_{SH}$ | $R_\theta/R_0$ |
|---|---|
| 40 | 0.99 |
| 50 | 0.84 |
| 60 | 0.73 |
| 70 | 0.65 |
| 80 | 0.58 |
| 90 | 0.52 |
| 100 | 0.48 |
| 110 | 0.44 |
| 120 | 0.40 |
| 130 | 0.37 |
| 140 | 0.35 |
| 150 | 0.33 |
| 160 | 0.31 |
| 170 | 0.29 |
| 180 | 0.28 |

# 3 Outline design guidance

## 3.1 Applicability of guidance

This design guidance is intended to be applied to the outline design of nearshore detached breakwaters for beach erosion control on relatively straight sandy shorelines (initial condition) subject to tidal action up to macro-tidal range.

The guidance is intended for application at option appraisal stage in order to assist with decision making regarding suitable approaches for managing beach levels. The guidance only provides advice on determining the parameters required to develop a preliminary geometrical layout. If, following appraisal of other options, a breakwater scheme is selected as a preferred option then further, more detailed, site specific feasibility studies would be required in order to develop a preliminary design.

The guidance is intended to be applied by experienced coastal engineers and requires skill and experience to interpret the input and output parameters.

It is assumed that, as a minimum, a preliminary assessment of coastal processes, including evaluation of trends in beach behaviour and assessment of the local sediment budget, will have been undertaken prior to use of this guidance. For this guidance to be applicable, coastal process assessment will already have identified a long term problem with beach erosion that could be addressed using beach control structures.

### 3.1.1 Outline design parameters for the subject site

In order to apply the guidance, a reasonable knowledge of the prevailing conditions at the potential site for the scheme is required.

Prior to outline design, a general assessment of coastal processes along the shoreline segment to be protected should have been carried out. This assessment needs to provide an understanding of the sediment transport processes, erosion/accretion and historical morphological development taking place at the site. For sites in the UK, this would often begin by assessing baseline information contained in the Shoreline Management Plan for the area and in previous coastal process studies.

In order to proceed with this guidance, it is necessary to have gathered data on waves, tides, sediment characteristics, and the existing nearshore bathymetric and beach profiles at the location.

The required beach and shoreline response (salient, tombolo) needs to be established before applying this guidance. This involves considering a number of factors, including, for example, impacts on the wider coastal environment, the desirable beach width and crest elevations. For further guidance the reader should refer to the *Beach management manual* (CIRIA 1996), which is presently under revision.

The outline design[4] of a nearshore detached breakwater scheme on a sandy coast consists of specifying the key geometrical parameters of the breakwater scheme in order to obtain a desired response under the prevailing wave and tidal conditions at the

[4] Also known as functional design in literature from North America, as it relates to the design of the breakwater scheme for serving the function of protecting a section of the shoreline.

specified beach. The key geometrical parameters to be specified in outline design are (see Figure 2.1):

- the length of the breakwater, $L_S$, measured along the breakwater crest;
- the cross-shore distance of the breakwater relative to a characteristic initial shoreline (MSL shoreline), X;
- the gap distance between adjacent breakwaters, G, measured as the gap distance between the breakwater crests;
- the breakwater crest elevation, $h_{cr}$, measured relative to MSL and the breakwater crest width, B.

Further guidance on selecting the input parameters is given in the worked examples presented in Chapter 4, see Table 4.1.

## 3.2 Existing guidance

Existing design guidance has focused on providing empirical relationships or design curves between key geometrical parameters of the breakwater scheme and the expected beach response. The beach response is typically characterised in terms of accretion in the lee of the breakwater (see Table 2.1) and erosion at the shoreline between the breakwater gaps.

A method for conducting the outline design of a breakwater scheme using existing design curves is provided by Fleming and Hamer (2000), hereafter FH2000, and illustrated in Figure 3.1.

STAGE 1: Determine X from amount of longshore transport to be bypassed to downdrift beaches.

**Fix X by reference to sediment pathways.**

↓

STAGE 2: Determine $L_S$ based on desired beach response (salient or tombolo).

**Use Figure 3.2 to determine $L_S$/X and hence determine $L_S$.**

↓

STAGE 3: Determine G (gap width) based on erosion in breakwater bays.

**Use Figure 3.3 to determine G/X and hence determine G.**

**Figure 3.1 Outline design procedure suggested by Fleming and Hamer (2000).**

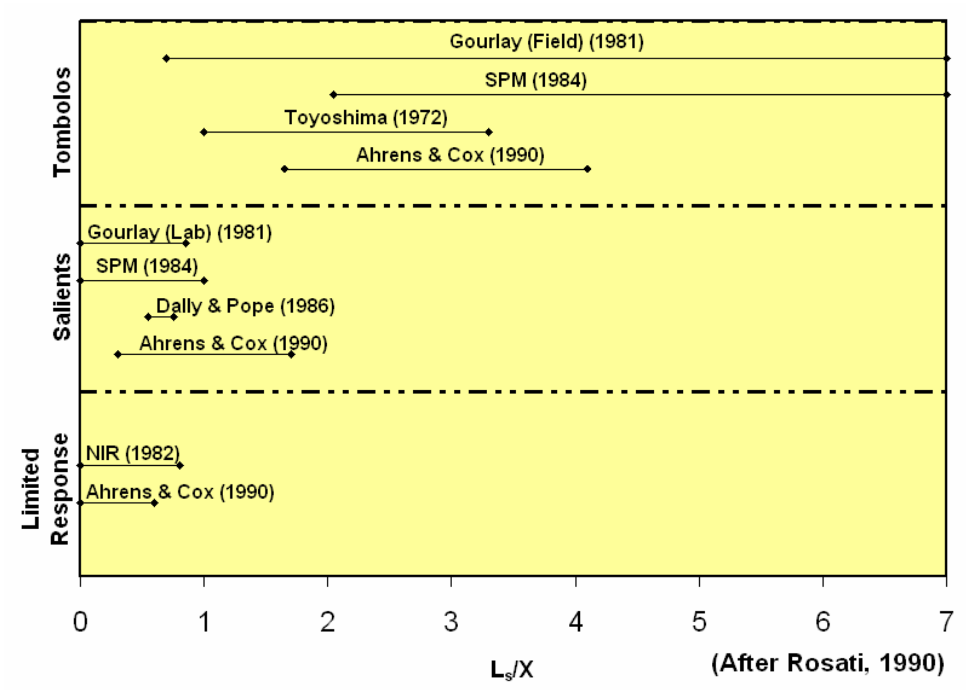



**Figure 3.2 Existing design guidance for determining shoreline response in the lee of detached breakwaters.**

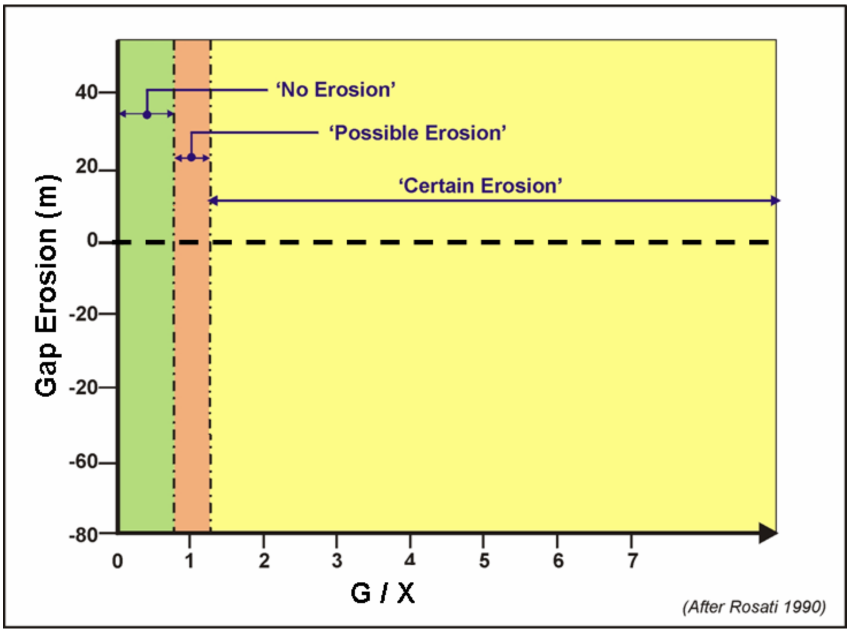



**Figure 3.3 Existing design guidance for assessing possible shoreline erosion in the gaps between nearshore breakwaters[5].**

In this method, the outline design of the breakwater scheme consists of specifying the three parameters X, $L_S$ and G using existing design curves, which are mainly based on laboratory experiments and limited field data from micro-tidal sites. It is noted that

[5] In the original figure from Rosati (1990), the erosion in the breakwater gap (gap erosion) for a number of breakwater cases in the US are also plotted. This has been omitted here for clarity.

these design curves, while useful, omit other parameters that affect the morphological response in the vicinity of breakwaters. These include the effect of wave climate, breakwater crest level and tides. Furthermore, these curves are derived for emergent breakwaters. Pilarczyk and Zeidler (1996) provided some additional guidance for submerged breakwaters, which considers the effect of wave transmission over the breakwater. However, no design guidance is available for meso- and macro-tidal sites.

## 3.3 New guidance

A new procedure for the outline design of detached breakwater schemes on sandy shorelines is shown schematically in Figure 3.4. This procedure is similar to that suggested by FH2000 with two key differences – namely:

(a) it makes use of the indicative outline design curves presented in Chapter 2; and

(b) it includes the effect of tidal range and submergence of the breakwater crest.

The effect of tidal range and submergence of the breakwater crest is an important consideration for predicting shoreline response at the outline design stage. For example, when the breakwaters are frequently submerged and located close to the shoreline, a smaller salient will be generated due to the erosive action of water flowing over the breakwaters and returning between the breakwater gaps.

STAGE 1: Determine X from amount of longshore transport to be bypassed to downdrift beaches.

**Fix X by reference to sediment pathways.**

↓

STAGE 2: Determine $L_S$ based on desired beach response (salient or tombolo).

**Use equation 2.1 to determine $L_S/X$ for no tides. Use Figure 2.3 to determine salient extent (S) including the effect of tides.**

↓

STAGE 3: Determine $h_{cr}$ (breakwater crest level) based on required salient extent, S.

**Use Figure 2.4 to determine $d_{cr}/H_{m0}$, and hence breakwater crest level. (Note: result should be taken with caution if $R/H_{m0}$ >2.5.)**

↓

STAGE 4: Determine G (gap width) based on maximum erosion in breakwater bays.

**Use Silvester and Hsu equation (2.2) to predict MSL shoreline in the bay (only for large gap widths) OR use existing guidance as in FH2000.**

**Figure 3.4: Schematic representation of new outline design procedure.**

The procedure schematised in Figure 3.4 is further elaborated below.

- Stage 1: Fix the offshore distance by reference to the amount of longshore sediment transport that should be bypassed to down-drift beaches in order to minimize down-drift erosion. In general, the amount of transport bypassed to downdrift beaches (downdrift of the breakwater scheme) reduces as $X/X_b$ increases.

- Stage 2: Once the optimum offshore distance of the breakwater has been determined, it is then straightforward to calculate $X/X_b$. Next, using the relationships determined in this study, calculate the breakwater length ($L_s$) for the desired beach response (in the lee of the breakwater), including the effect of tidal range, as shown in Figure 2.3.

  Decisions will need to be taken regarding the preferred beach response (limited response, salients or tombolos). Clearly, tombolos will be more disruptive than salients to the longshore movement of sediment, but will offer more protection during severe storms[6] and offer a greater amenity area.

- Stage 3: Determine the breakwater crest level based on the desired salient length using the design graph shown in Figure 2.4. In general, the salient width (and also the beach level) reduces as the depth of water over the breakwater crest at high water increases.
- Stage 4: Lastly, estimate the gap width between the breakwaters based on the maximum shoreline erosion (MSL shoreline) allowed in the breakwater bays. This is done using either the Silvester and Hsu equation (2.2 above) for beach planform (if it is intended that the gap width should be large) or, alternatively, the existing design curves (such as Figure 3.3).

  Note that the effect of the breakwater gap width was not investigated in the present study. In general, the shoreline erosion is expected to increase as the gap width increases, until the gap width is large enough that each breakwater can be considered to be independent of the adjacent one.

Two worked examples illustrating the above procedure are presented in Chapter 4.

## 3.4 Structural design of breakwaters

Detached breakwaters are normally built as rubble-mound structures. They may typically be constructed from rock armour, or from proprietary concrete armour units designed to interlock and efficiently dissipate wave energy. Alternative forms of construction that have been considered for use in beach stabilisation reefs include large geotextile sand bags, sunk scrap barges and small ships, scrap sections of offshore oil industry structures and scrap tyre reefs. However, no attempt to assess the viability of any of these alternatives has been attempted under this project.

This project and the design guidance focus on the geometric layout of beach control breakwater systems rather than the structural design of breakwater structures. Other guidance should be referred to for structural design. For example, the design of rock armour breakwater cross-sections is dealt with in the *Rock manual* (CIRIA/CUR 2007). The *Coastal engineering manual* (USACE 2003) describes the design of both rock armour and concrete armour units. In the UK, it is usual to refer to BS6349 Part 7 for the design of concrete armour units, as well as proprietary information from those companies that license the use of specific armour units.

[6] This is because a tombolo provides a wider area for wave energy dissipation and more sand needs to be eroded from such a feature compared to a salient (assuming the same offshore location of the breakwater).

# 4 Worked examples

In this chapter, two worked examples for determining the geometrical parameters of a breakwater scheme are provided to illustrate the new outline design procedure proposed in this guidance report.

In Table 4.1, some suggestions are given for defining the characteristic parameters that determine the wave and tide conditions at a given site. These characteristic parameters are used in the design curves for estimating the geometrical parameters of the breakwater scheme. A list of the parameters used in the worked examples is given in Table 4.2.

**Table 4.1 Parameters for determining incident wave and tide conditions used in the design curves.**

| Parameter | Suggestion | Further remarks |
|---|---|---|
| $H_b$ | Determine $H_b$ based on the $H_{m0}$ exceeded 12hr/year at the site, calculated at the closure depth. | $H_{m0}$ exceeded 12hr/year is the characteristic wave height used to determine the closure depth (limit of littoral drift movement) and can be considered as characteristic for determining the area affected by the littoral drift.<br><br>$H_b$ is used as the characteristic $H_{m0}$ to determine the dimensionless tidal range ($R_{tide}/H_{m0}$) and the submergence depth ($d_{cr}/H_{m0}$) in the design curves. |
| $X_b$ | Determine $X_b$ based on $H_b$ determined as above and the average beach slope. | |
| $R_{tide}$ | Use the difference between the MHWS (mean high water spring) tide level and MLWS (mean low water spring) tide level. | A spring tidal cycle occurs every fortnight, and thus it is likely that significant storms for sediment transport will occur during spring tides. Hence, this is considered as the appropriate parameter to use in outline design. |
| $d_{cr}$ | This is defined as the submergence depth at high water during a typical annual residual surge level:<br><br>$d_{cr}$=MHWS + $Surge_{1yr}$ – $h_{cr}$<br><br>$Surge_{1-yr}$ = surge level with return period of one year and $h_{cr}$ = elevation of breakwater crest level. | Although the numerical model simulations do not include the effect of residual surge level, it is expected that this will be important in practical situations, given that the numerical simulation results show significant impact on the submerged depth at the breakwater crest level. |

**Table 4.2 Parameters used in worked examples.**

| Parameter | Units | Description |
|---|---|---|
| $C_g$ | m/s | Wave group velocity |
| $d_{cr}$ | m | Depth of water at the breakwater crest during high water |
| G | m | Gap width between breakwaters |
| $h_{cr}$ | m | Height of breakwater above mean sea level |
| $H_b$ | m | Characteristic significant wave height at the closure depth |
| $H_{m0}$ | m | Significant wave height |
| $L_s$ | m | Breakwater length |
| MSL | m | Mean sea level |
| $R_{tide}$ | m | Tidal range |
| S | m | Salient length |
| $T_p$ | s | Peak wave period associated with $H_b$ |
| X | m | Distance from baseline to breakwater centre line |
| $X_b$ | m | Distance from baseline to closure depth |

## 4.1 Example 1

Problem:
Investigate the feasibility of a breakwater scheme on a 1000m section of an eroding shoreline by determining the outline design of a breakwater scheme (Ls, X, G, $h_{cr}$), given the information below.

- $H_{m0}$ exceeded 12 hrs/yr in deep water = 4.0m
- Associated wave period, $T_p$ = 10s
- Main wave direction = 15$^o$ to shore normal in deep water
- Spring tidal range= 3m and MHWS = 1.5m relative to MSL
- 1yr surge = 1.0m
- Average beach slope: 1:30
- Estimated depth of closure = 7m relative to MSL
- 50 per cent of incoming longshore transport is desired to be bypassed to downdrift beaches and a tombolo response is desired at the breakwater[7].

The calculations are summarised in Table 4.3.

[7] This implies that the tombolo in the lee of the breakwater would be formed by the 50 per cent of the incoming longshore transport that is trapped in the lee of the breakwater.

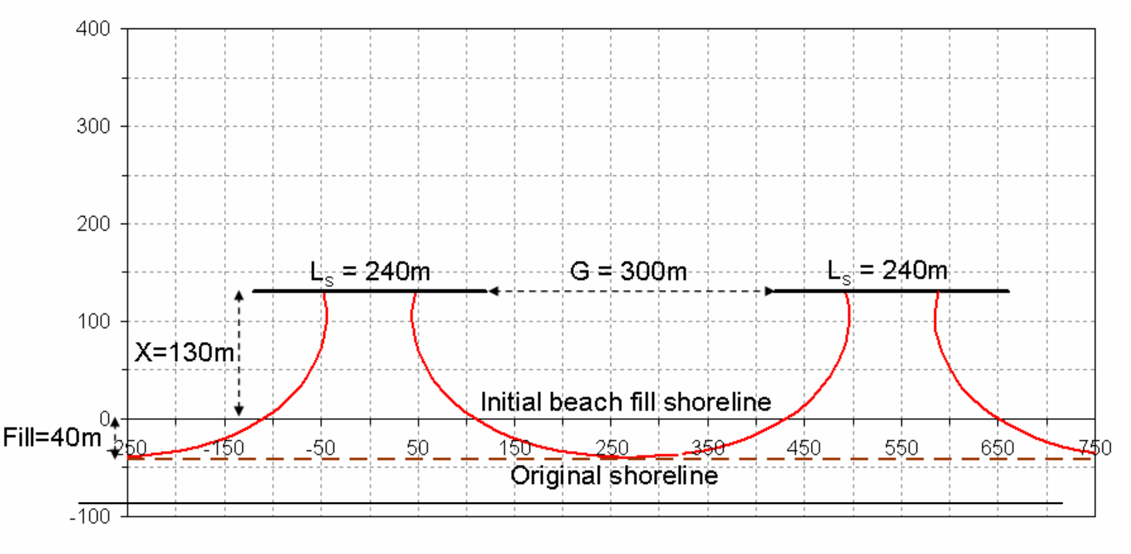
**Table 4.3 Calculations for worked example 1.**

| Calculations | Results |
|---|---|
| <u>Stage 1: Breakwater location calculations</u><br>1.1. Given $H_{m0}$ exceeded 12hrs/yr in deep water, determine the corresponding $H_{m0}$ at depth of closure (and water level at MSL).<br>At MSL, the given water depth at the closure depth is:<br>depth = 7m.<br><br>Use conservation of energy equation for shore parallel contours and assume shore normal waves (conservative assumption).<br>$H_{m0}^2 C_g =$ constant<br>$H_{m0,7m} = H_{m0,deep\ water} * \sqrt{C_{g,deep\ water} / C_{g,7m}}$<br>= 4 * sqrt (7.8 / 7.3) = 4.1m<br><br>Check if $H_{m0}$ is depth limited at closure depth during high water (HW)<br>At HW, the water depth at the closure depth is:<br>depth = (7+1.5+1)m = 9.5m.<br>max $H_{m0}$ = 0.5 * depth = 4.75m.<br>Therefore, waves are not depth limited at closure depth. | |
| 1.2. Estimate $X_b$ as equal to the distance to closure depth.<br>$X_b$ = closure depth / beach slope = 7 * 30 = 210m | $X_b$ = 210m from MSL |
| 1.3 Determine X based on percentage of longshore transport to be bypassed. Ideally, we should use a simple tool such as LITDRIFT, COSMOS-2D or UNIBEST-LT to determine distribution of littoral drift across the littoral zone. | |
| Here, we have assumed that $X/X_b$=0.6 gives 50 per cent bypassing[8]. Thus, X = 0.6 * 210m = 126m. Use X = 130m. | X = 130m. |
| Therefore depth at structure = 130 / 30 = 4.3m relative to MSL.<br>Max $H_b$ at structure = 0.5*depth at HW = 0.5 * (4.3+1.5+1.0) = 3.4m.<br>Therefore, waves at the structure are depth limited, as this wave height is less than the estimated incoming wave height at closure depth ($H_{m0}$ = 4.1m at closure depth). | $H_b$ = 3.4m. |
| <u>Stage 2: Breakwater length and accretion calculations</u><br>2.1. Determine $L_s$ for non-tidal beaches, given that tombolo response is desired; use equation 2.1.<br>$L_s / X > 2.8 – 1.6(X/X_b) = 1.84$<br>or $L_s$ > 1.84 *130 = 239m. Use $L_s$ = 240m. | $L_s$ = 240m |
| 2.2. Include effect of tidal range (assuming emergent breakwaters) on salient response using Figure 2.3. | |
| From the calculation in step 2.1 above, $L_s/X$ = 1.84, which is greater than 1.3. Thus, the effect of tidal range on the beach response is | Tidal effect negligible for this case. |

8 This assumption is based on the simulation carried out for the generic test case 02. Note that this is not a general rule and will vary during the application for a given site, depending on various things such as beach profile and sediment characteristics.

| Calculations | Results |
|---|---|
| expected to be negligible (emergent breakwaters). | |
| <u>Stage 3: Crest level calculations</u><br>3.1 Determine crest level of breakwater.<br>In Figure 2.4, use curve for $L_s/X = 1.33$.<br>(Note: $R/H_{m0} = 3 / 3.4 = 0.9 < 2.5$, ok).<br><br>By extrapolation in Figure 2.4 and taking S/X=1.0 for tombolo, $d_{cr}/H_{m0}=0.05$.<br>Therefore, $d_{cr} = 0.05*H_{m0} = 0.05 * H_b = 0.05*3.4 = 0.17$m.<br><br>Breakwater crest level, $h_{cr}$ = MHWS + 1yr surge – $d_{cr}$<br>= 1.5 + 1.0 – 0.17 = 2.33m. Use $h_{cr}$ = 2.4m relative to MSL. | Breakwater crest level, $h_{cr}$ = 2.4m MSL |
| <u>Stage 4: Gap width and erosion calculations</u><br>4.1 Determine gap width, G<br>Determine maximum erosion at gap width using Silvester and Hsu parabolic bay shape, assuming the effect of adjacent breakwaters are independent of each other. This is typically the case if the gap width is about five wavelengths or greater.<br><br>Wavelength at depth of 4.3m and Tp=10s = 63.9m.<br>Therefore G = 5 *64m = 320m.<br>Use G = 300m (conservative, lower erosion).<br><br>Determining the maximum shoreline erosion using Silvester and Hsu parabolic bay shape method gives maximum erosion = 37.4m.<br><br>Therefore, a minimum beach fill of 40m width should be provided.<br><br>Notes:<br>1. The design curves are derived for waves with normal incidence. It is expected that the location of the tombolo will be shifted slightly downdrift for oblique wave incidence. | G= 300m<br><br>Initial beach fill=40m. |

Outline design summary:




$L_s$ = 240m, X = 130m, G = 300m, $h_{cr}$ = +2.4m MSL and required beach fill=40m crest width at MSL. Beach response = tombolo.

## 4.2 Example 2

Problem:
Determine the potential reduction in the salient extent if the crest level of the breakwaters in Example 1 is reduced to +1.2m MSL. The calculations are summarised in Table 4.4.

**Table 4.4 Calculations for worked example 2.**

| **Calculations** | **Results** |
|---|---|
| <u>Stage 3: Breakwater crest level calculations</u><br>3.1 Determine submergence depth at HW<br>$d_{cr}$ = MHWS + 1yr surge – $h_{cr}$ = 1.5 + 1.0 – 1.2 = 1.3m | |
| 3.2 Determine $d_{cr}$ / $H_{m0}$<br>$d_{cr}$ / $H_{m0}$ = 1.3 / 3.4 = 0.38 | |
| 3.3 Determine salient length from Figure 2.4<br>In Figure 2.4, use curve for $L_s$/X = 1.33.<br>Using $d_{cr}$ / $H_{m0}$ = 0.38 in Figure 2.3 gives S/X =0.65. | |
| Therefore, the salient length, S = 0.65*X = 0.65 * 130 = 84.5m.<br>Use S = 84m relative to MSL shoreline. | Salient length,<br>S = 84m |

Notes:

1. The design curves are derived for standing tides, and the salient lengths will be expected to be smaller for progressive tides.
2. The beach levels (relatively flat section of the beach profile in the lee of the breakwater) are lower with reduced breakwater crest level. No design curve is available to estimate beach level.
3. Figure 2.4 shows that the effect of the relative submergence depth increases with increasing $L_s$/X. Thus, it is likely that the effect of the reduced crest level on salient length may possibly be greater (the reduction in salient length may be more for $L_s$/X=1.84) than is estimated using a design curve for $L_s$/X = 1.33.

Outline design summary:

$L_s$ = 240m, X = 130m, G = 300m, $h_{cr}$ = +1.2m MSL and required beach fill=40m.
Beach response = salient.

# 5 Tools for detailed analysis

The guidance outlined in Chapter 3 provides a simple and quick method for preparing the outline design of a detached breakwater scheme on a macro-tidal coast. However, after selecting a detached breakwater scheme, further study and analysis should be carried out to confirm and optimise the outline design before progressing to the detailed design stage.

In this chapter, a brief description of the available tools for detailed analysis of the impact of detached breakwaters on macro-tidal coasts is given. The main tools are:

- field observations;
- laboratory (physical) modelling;
- numerical modelling.

These are described in the sections below.

## 5.1 Field observations

Large EU projects, such as COAST3D and INDIA (Soulsby 2000, Williams *et al.* 2003), have demonstrated the advantages of using new types of equipment, such as video, acoustic and radar technologies, to monitor the open beach environment during storm conditions and over the medium term. The LEACOST2 project has also demonstrated the use of these techniques to monitor the shoreline evolution at Sea Palling, Norfolk (see papers A1 through A3 in Appendix A of the companion science report).

If detailed observations of the morphological response to the impact of a breakwater scheme are available at a nearby coast with the same wave exposure, tide and sediment characteristics, this information can be used to determine the detailed beach response to a similar breakwater scheme at a new site.

Note that if such detailed field observations are available, it will be unnecessary to use this design guidance for outline design, as the field observations can be used directly. However, in most cases, the conditions are not exactly similar, and other techniques are required in order to estimate the beach response.

## 5.2 Laboratory modelling

In its general form, laboratory (physical) models are small scale representations of a given prototype, in which the similarity between key dimensionless parameters in the small scale representation and the prototype are ensured.

It is usually difficult to ensure strict similarity between small scale models of the morphological evolution of sandy beaches (mobile bed models) and the prototype. This lack of similarity results in what is commonly termed the 'scale effect', which is directly related to the scaling of the prototype. Special techniques have been developed in order to cope with scale effects in mobile bed models and to make the results useful for predicting prototype behaviour. More detailed discussion on scaled laboratory models can be found in several publications, for instance Kamphuis (1985), Hughes (1993) and Soulsby (2008).

Scale effects make it difficult to extrapolate the findings of small scale models on morphological evolution to prototype conditions. However, such models are still used, although expert judgement is required in order to derive a proper interpretation of the prototype from the laboratory scale model.

Nevertheless, there are advantages of using a physical model at a suitably designed scale and these are detailed below.

- The natural generation of non-linear shallow water effects, such as skewness and asymmetry, and wave-wave interactions, such as quadruplets and triads.
- Natural dissipation of energy by depth-limited breaking, whitecapping and seabed friction.
- Natural reproduction of refraction by changes in seabed level.
- Reproduction of transmission through and over the breakwater (after careful scaling of the model core and armour).
- Natural generation of diffraction, which is a key physical process in the generation and limitation of salients.
- Natural generation of wave-breaking induced longshore currents.
- Includes cross-shore processes, such as undertow, that can lead to onshore-offshore sediment transport.
- Representative spectra of irregular waves are generated in a physical model, rather than a single representative wave.
- Wave-structure interactions occur, which may result in local scouring and deposition. This can interact with the structure, promoting damage to the toe of the breakwater in places, or can cause damage to the armour as a result of overtopping.
- Damage to the breakwater can be measured and the breakwater stability can be assessed.
- In coarse sediments, porosity effects can be included.

## 5.3 Numerical modelling

In their general form, numerical models are mathematical representations of the processes in a given prototype. For predicting future beach performance, the numerical model should represent at a sufficient level of detail the important coastal processes responsible for beach changes. The companion science report (Environment Agency 2009) contains a description and discussion of key coastal processes and their representation in two state-of-the art coastal area morphological models.

Beach changes result from changes to sediment transport rates, which are in turn related to the waves and currents affecting the coast. Hence, all process-based numerical models for predicting beach changes will include models for predicting waves, flow and sediment transport and for solving a continuity of sediment mass equation to determine the beach changes.

It is important to note that there can be significant differences in the description of the physical processes in different models, which may in turn affect the results. The sophistication of a coastal area model depends on the level of detail used to represent the coastal processes. For example, the wave transformation model in some models may include random waves and wave diffraction, while in others this may not be the case. In order to check the accuracy and robustness of a coastal area morphological model, the calibration and validation of the model system (as individual process models and as a coupled integrated morphological model) against historical data (wherever practicable) is an important part of the beach evolution modelling study. The model calibration and validation should precede its use for predicting future beach performance at the detailed design stage. In addition, the model selection should follow a detailed appraisal of the key processes that need to be represented.

The most detailed numerical model for determining beach response in the vicinity of a detached breakwater is a coastal area morphological model. Coastal area morphological models can be used to predict the impact of a given breakwater scheme on a specified shoreline and nearshore area in the medium term (from months to a few years). They are valuable for providing insight into the two-dimensional modifications of wave, flow and sediment transport conditions near the coast, especially in areas of complex bathymetry or in the vicinity of coastal structures. This information can also be used in other aspects of beach planning; for instance, to delineate areas with strong currents that may be dangerous for swimmers.

Morphological models include feedback of bathymetry changes in the constituent process models. For a given initial bathymetry and boundary wave conditions, the process models are used to simulate waves, flow and sediment transport. The resulting bed level changes are calculated and the new bathymetry is fed back to the process models for another round of calculations at another time step. This process is repeated in sequence until the prediction covers the required period.

Examples of commercially available coastal area morphological models include: Delft3D MOR, developed by Deltares, the Netherlands; MIKE 21 CAMS, developed by DHI Water and Environment, Denmark; PISCES, developed by HR Wallingford, UK. Significant progress has been made in the development of coastal area morphological models since the mid-1990s, with very promising results. Examples of recent studies include Zyserman *et al.* (2005), Sutherland *et al.* (2004) and Lesser *et al.* (2003).

Numerical coastal area morphological models are complex and typically require a technical expert to carry out the modelling study and interpret the results for practical use. Moreover, numerical models do have weaknesses, as they are limited by the accuracy of the mathematical representation of the important morphological processes in the model. However, they are still a very useful tool for efficiently investigating a variety of layouts when combined with expert judgement in order to derive a proper interpretation of the prototype from the numerical model.

# 6 Conclusion

This research has achieved its objective of providing coastal practitioners with guidance for the outline design of a nearshore detached breakwater scheme for beach erosion control on a sandy coast. This report provides improved design guidance, which includes the effect of tides (up to macro-tidal range), the width of the surf zone, breakwater crest level and other geometrical parameters. The design guidance is based on the results of the coastal area morphological modelling study presented in the companion science report (Environment Agency 2010).

This design guidance is intended for application at the option appraisal stage to assist in decision making regarding suitable approaches to managing beach levels. If a breakwater scheme option is selected after considering this guidance, more detailed analyses should then be carried out for the particular site to develop a preliminary design and to confirm the breakwater layout before carrying out a detailed design. Some advice on selecting approaches for these detailed analyses has been included. The guidance in this report is intended to be applied by experienced coastal engineers and requires skill and expertise to interpret the input and output parameters.

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