Modelling morphological changes associated with an offshore breakwater

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Abstract

A morphological model, comprising a suite of wave and current, sediment transport and bed level change modules, is applied to a hypothetical offshore breakwater layout. The accuracy of the morphological changes predicted by the model is then checked using available laboratory and field data.

1 Introduction

Engineering works on sandy coastlines disturb the local sediment transport pattern and consequently generate changes in the local morphology. There is, therefore, a need to be able to predict such changes and, in recent years, this has led to the development of a range of morphological models (see, for example, De Vriend et al. [5]). Much of the latest work on these models has suggested the need to include the effects of wave-current interaction, the influence of bed slope on the sediment transport and hydrodynamic-morphodynamic feedback. The present paper describes the application of one such model to a typical offshore breakwater layout with the object of demonstrating the usefulness of the approach for engineering design.

2 Model Description

The model consists of three components, namely a combined wave and current sub-model, a sediment transport sub-model and a bed level change sub-model. The wave component of the first sub-model solves the current-affected kinematic and energy conservation equations for wave height and direction while the current component solves the shallow water equations with added wave terms (Yoo and O’Connor [17]). Allowance is made for the effects of
interactive wave-current friction, wave breaking, shoaling, refraction, diffraction and full wave-current interaction. The governing equations use a variety of turbulence closures, that based on the Battjes approach, as modified by O'Connor and Yoo [10], being used in the present application. In addition, long-crested random waves are simulated using the Battjes and Janssen [1] equivalent, monochromatic wave approach, the associated breaker criterion being that of Nairn [9]. The second sub-model, that concerned with sediment transport, computes the combined suspended and bed load sediment fluxes. This computation takes place in two stages, the first stage concerning the determination of the suspended sediment transport rate using an empirical expression for the potential load due to waves and currents (unpublished) and the second stage concerning the determination of the bed sediment transport rate using the Einstein approach, as modified by Bijker [2]. Finally, the bed level change sub-model solves the sediment flux divergence equation, using a modified Lax-Wendroff scheme. The sediment flux divergence equation includes a gravitational term to allow for transport on slopes and takes the form suggested by Watanabe [16]:

$$\frac{\delta z_B}{\delta t} = \frac{1}{(\rho_s(1-p))} \left[ -\frac{\delta}{\delta x} \left( Q_x - \alpha |Q_x| \frac{\delta z_B}{\delta x} \right) - \frac{\delta}{\delta y} \left( Q_y - \alpha |Q_y| \frac{\delta z_B}{\delta y} \right) \right]$$  \hspace{1cm} (1)

where \(x, y\) = longshore and cross-shore co-ordinates respectively (m); \(\alpha\) = positive coefficient; \(Q_x, Q_y\) = longshore and cross-shore components of the sediment flux respectively (kg/m/s); \(\rho_s\) = sediment density (kg/m³); \(\rho\) = porosity of the bed material; \(z_B\) = bed elevation (m). Watanabe [16] does not recommend a value for \(\alpha\) but suggests that it be determined empirically; intuitively, a value of approximately unity seems most appropriate.

The time-stepping mechanism of the model involves two nested loops, during the inner of which the hydrodynamics is partly updated and during the outer of which the hydrodynamics is completely updated. The time step associated with the inner loop is controlled by a Courant criterion, which is based on the rate of propagation of a bed disturbance, while that associated with the outer loop is controlled by a limiting depth change criterion.

Provision is made in the model for the effects of underwater avalanching. This particular phenomenon is considered to occur whenever an underwater bed slope exceeds the angle of repose of the bed material. The underwater angle of repose is given by Shibiyama and Horikawa [12] as:

$$\beta_U = 0.47(D_{50})^{1/8}(\rho_f/\rho_s - 1)^{0.19}$$  \hspace{1cm} (2)

where \(\beta_U\) = underwater angle of repose; \(D_{50}\) = median grain size (mm); \(\rho_f\) = fluid density (kg/m³).
The model does not include the effects of cross-shore transport and hence its range of application is limited to situations wherein sediment transport due to depth-mean currents dominates that due to undertow. Examples of situations which fall into this category are morphological changes at any time scale induced by offshore structures and long-term changes associated with other coastal features.

3 Test Conditions

The model was tested initially on a variety of layouts and shown to give similar results to those produced by other morphodynamic models (De Vriend et al. [5]). For present purposes, the model was tested further on the prototype-scale offshore breakwater layout shown in Figure 1. This particular configuration was adopted because it contains all the important coastal hydrodynamic processes, namely shoaling, friction, refraction, diffraction and wave-generated currents; in addition, sediment transport due to depth-mean currents is more important than that due to undertow. The breakwater was founded on a plane sloping beach and subjected to the action of normally-incident, long-crested, random waves. Values adopted for parameters, which were not altered during the course of the test programme, were as follows:

- $d_B = \text{water depth at the seaward edge of the breakwater} = 4.6\text{m}$
- $D_{50} = \text{median grain size} = 250\mu\text{m}$
- $H = \text{incident wave height} = 2.0\text{m}$
- $i = \text{bed slope} = 1:50$
- $k = \text{bed roughness} = 0.025\text{m}$
- $T = \text{peak energy wave period} = 8.0\text{s}$
- $x_B = \text{breakwater distance offshore} = 240\text{m}$
- $y_B = \text{breakwater length} = 300\text{m}$
- $\Delta x = \Delta y = \text{mesh size of the model grid} = 10\text{m}$.

The test programme comprised a sensitivity analysis which involved the coefficient ‘$\alpha$’ in the gravitational transport term (see Eqn. (1)) and the influence of underwater avalanching. A summary of the test conditions is contained in Table 1.

<table>
<thead>
<tr>
<th>Run</th>
<th>$\alpha$</th>
<th>Underwater Avalanching</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>No</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
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</tr>
<tr>
<td>3</td>
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<td>No</td>
</tr>
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<td>1.0</td>
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</tr>
</tbody>
</table>
4 Test Results

The initial wave-generated current vectors and wave amplitudes produced by the model are set out in Figures 2 and 3 respectively. Figure 2 shows the existence of two counter-rotating gyres in the lee of the breakwater, each of which drives a much weaker gyre located further along the coastline. Figure 3 indicates the extent to which the combined effects of wave diffraction and current refraction modified the wave field in the lee of the breakwater by generating wave action in this area.

Similar bathymetric changes were produced during all four tests. Typical results, those for Test 2, are contained in Figures 4a to 4c which show the bathymetry after 3, 11 and 50 days of wave action respectively. In general, the bathymetric changes consisted of the formation of two spits which advanced towards, and ultimately became attached to, the landward side of the breakwater. The space between these two spits then filled up, thereby forming a tombolo. Another noticeable morphodynamic feature, again common to all tests, was the existence of two scour holes. These appeared during the early stages of a test on the landward side of the breakwater and then progressed steadily towards each breakwater tip, in the process becoming larger and deeper.

5 Discussion

The accuracy of the hydrodynamic predictions was checked using laboratory data (Mory and Hamm [8]) which are depicted in Figure 5. The laboratory data were measured in a fixed-bed wave basin, which contained a 1 in 22.5 version of the prototype-scale layout and regular waves. In spite of these differences, a comparison of Figures 2 and 5 indicates a close qualitative resemblance between the two current patterns. The centre of each gyre and the maximum velocity were located in the same position in each case and the maximum velocities agreed to within 20 per cent.

A qualitative check on the accuracy of the morphological predictions was made by establishing whether a salient or a tombolo should form under the test conditions in question. Information contained in the literature, however, is contradictory regarding the occurrence of these two features. The US Army Corps of Engineers [15], for example, states that:

\[
\frac{y_B}{x_B} < 1.0 : \text{salient} \\
1.0 < \frac{y_B}{x_B} < 2.0 : \text{salient or tombolo} \\
\frac{y_B}{x_B} > 2.0 : \text{tombolo}
\]

Suh and Dalrymple [13] and Tarnowska and Zeidler [14], on the other hand, concluded that a \(\frac{y_B}{x_B}\)-ratio of 1.0 separates salients from tombolos while
values of 1.3, 1.5 to 2.0 and 2.0 are given, respectively, by Hsu and Silvester [7], Dally and Pope [3] and Dean [4]. In the present situation, \( y_B/x_B \) has a value of 1.3 and hence the model, in predicting the occurrence of a tombolo, satisfied four of the above criteria and violated only two. In addition, the work of Rosen and Vajda [11] indicates that a tombolo is likely to form if the breakwater is located within the surf zone, a criterion which is adhered to in the present situation. On balance, therefore, it is concluded that the model produced the correct form of deposition behind the breakwater.

A quantitative check on the accuracy of the morphological predictions was also carried out by comparing the computed, steady-state volume of deposition behind the breakwater with an empirical expression for this quantity. The empirical expression for the deposition was developed by Harris and Herbich [6], using laboratory and field data, and takes the form:

\[
Q_B = \exp\{0.31 - 1.92(x_B/y_B)\}
\]

(4)

where \( Q_B \) = volume of sediment moving into the sheltered area behind the breakwater (m\(^3\)). For the layout simulated in the model, Eqn. (4) yields a \( Q_B \)-value of 97 000m\(^3\). The variation with time of the volume of deposition predicted by the model is shown in Figure 6. As can be seen, similar results were obtained for all test conditions, a steady-state having been reached after approximately 20 days, when the volume of deposition was 75 000 m\(^3\). This quantity agrees quite well with the 97 000 m\(^3\) yielded by Eqn. (4).

The relative merits of the morphodynamic predictions produced in the course of the sensitivity analysis were determined by examining the temporal changes in the maximum depth of erosion which are contained in Figure 7. The contents of the latter indicate that, in the absence of underwater avalanching, attributing a value of 1.0 to the coefficient '\( \alpha \)' in the gravitational sediment transport term (Test 1) led to an unrealistically large depth of erosion which oscillated with time. A similar trend was obtained when a higher \( \alpha \)-value of 3.0 was used (Test 3), although, in this case, the depth of erosion was smaller and hence more realistic. The most satisfactory outcome was achieved either by using an \( \alpha \)-value of 2 (Test 2) or by retaining an \( \alpha \)-value of 1.0 and, at the same time, including underwater avalanching (Test 4). Of these two alternatives, the former (Test 2) produced the smoother bathymetry and hence was deemed to be more appropriate for the present layout. However, it is envisaged that layouts involving the undermining and collapse of sandy cliffs, such as occurs at lagoon entrances, may be handled more satisfactorily by allowing for the effects of avalanching. A more detailed validation of the predicted accretion/erosion pattern has not yet been possible due to the lack of suitable field data.
6 Conclusions

A numerical model, which simulates morphological changes in the coastal zone, has been set up and tested on an offshore breakwater layout. Both the hydrodynamic and morphodynamic results produced by the model have been checked against available laboratory and field data. The results of this exercise indicated that the model yielded a wave-generated flow field which was in reasonable agreement with hydraulic model data and predicted global bathymetric changes which were both qualitatively and quantitatively correct. It was also found, for the layout examined, that the model yielded more realistic bathymetric changes if the coefficient in the gravitational component of the sediment transport rate were assigned a value close to two and the effects of underwater avalanching were neglected; the importance of including the gravitational term was also clearly demonstrated. The model, however, has yet to be validated against detailed bathymetric changes measured in the field. It is concluded, therefore, that the proposed scheme can be applied to real situations, provided that morphodynamic information is required on a global, rather than a local, basis.

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References

6. Harris, M.M. and Herbich, J.B. Effects of breakwater spacing on sand


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**Figure 1. Breakwater layout.**
Figure 2. Initial current vectors.

Figure 3. Initial wave amplitudes.

Figure 4a. Bed levels after 3 days.

Figure 4b. Bed levels after 11 days.

Figure 4c. Bed levels after 50 days.

Figure 5. Laboratory current vectors.

Figure 6. Breakwater deposition.

Figure 7. Maximum erosion.