ON THE DESIGN OF SHORE-PARALLEL BREAKWATERS

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Abstract

The morphological aspects of the design of shore-parallel breakwaters are investigated through a series of tests using a two-dimensional (in the horizontal plane) morphological modelling system. The analysis focuses on the optimisation of the breakwater length and its distance to shore in order to achieve the desired type of response. The results obtained are compared to empirical formulas from the literature and observations from the field.

Introduction

Shore-parallel breakwaters are frequently used in coastal protection and restoration schemes. An important aspect of the design of these structures is the prediction of the morphological response (i.e. the type of planform that will develop) in their vicinity. Depending on the intended purpose of the structure, a tombolo may be desired in some cases, whereas a stable salient behind the breakwater, without significant down-drift erosion, may be the preferred solution in other cases.

In this paper we concern ourselves only with the morphological aspects of the design of shore-parallel breakwaters. From this perspective, the design of the breakwater consists of defining appropriate dimensions for the length of the structure and its location in the nearshore area, in order to obtain the desired morphological response.

A coastal area morphological modelling system is applied to systematically investigate the morphological response behind a detached breakwater subjected to wave action. Tests are made with various combinations of breakwater length and distance from shoreline for given incident wave conditions, beach characteristics and sediment properties. The results of these tests are analysed to derive practical guidelines for the design of the structures.

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The following aspects of the study are discussed in the ensuing sections:

- the phenomena leading to the special planforms that are observed in the vicinity of detached breakwaters.
- the modelling system used to simulate the morphological evolution in the vicinity of shore-parallel breakwaters
- the test matrix defined on the basis of the findings from the dimensional analysis of the parameters controlling the morphological response
- presentation and discussion of the results

Processes in the vicinity of a detached breakwater

At a macro-scale level, the presence of the shore-parallel breakwater shelters the coast immediately behind the structure and the adjacent areas from the incoming waves. This means that the wave height at breaking will be smaller in the sheltered areas than elsewhere, which in turn will result in larger wave-induced set-up along the exposed beaches than in the sheltered areas.

The longshore variability in the wave set-up results in gradients of the mean water surface. These gradients tend to accelerate the longshore current flowing towards the sheltered area behind the structure and to change the direction of the current which is driven away from the breakwater by the breaking waves in the region immediately downdrift of the breakwater. The two current systems merge behind the structure, giving raise to complex circulation patterns.

The acceleration of the littoral current that takes place updrift of the shore-parallel breakwater causes initial erosion of the beach in that area. The same occurs in the area immediately downdrift of the structure. The currents carry the eroded material towards the sheltered area, where it deposits. These mechanisms cause the pattern of deposition behind the breakwater and erosion on either side of it that can be observed in nature.

The 2DH Morphological Modelling System

The coastal-area morphological modelling system applied in the present analysis was described in detail by Johnson et al. (1994). At that moment, the emphasis was placed on the selection of the wave model, the description of the bed roughness under combined waves and current, etc.

Briefly, the morphological modelling system is based on an explicit forward-time integration scheme for the evolution of the bathymetry. The system consists of a number of modules capable of reproducing the governing processes that were discussed in the previous section:

(i) a wave module, MIKE 21 PMS, based on the parabolic approximation to the mild-slope equation, used to calculate wave parameters as well as radiation stresses over the model area. MIKE 21 PMS accounts for the effects of shoaling, refraction, diffraction, breaking, directional spreading and bed friction on the incident waves

(ii) a hydrodynamic module, MIKE 21 HD, in which the flow field is found from the solution of the depth-integrated continuity and momentum equations. The currents driven by the breaking waves and the gradients in mean water level are calculated on a mobile bed evolving at the rate of dz/dt calculated by the sediment transport module

(iii) an intra-wave sediment transport module, MIKE 21 ST, accounting for the combined influence of waves and current on the transport rates of graded sediment

(iv) a bed level update scheme using an improved second-order Lax-Wendroff scheme

Further details on the morphological modelling system can be found in Johnson et al. (1994, 1995).

Dimensional Analysis and Test Matrix

Using dimensional analysis, Johnson et al. (1995) showed that the morphological response behind shore-parallel breakwaters on an initially plane beach can be expressed as a function of the dimensionless numbers ϕ_1 and ϕ_2 according to

$$\text{Morphological Response} = f(\phi_1 * \phi_2) \tag{1}$$

with

$$\phi_1 = \phi_1(H_b/L_0, \theta_b, m/(H_b/L_0)^{0.5}, H_b/d_{50}) \tag{2}$$

and

$$\phi_2 = \phi_2(t/T, X/X_{80}, L/X_{80}) \tag{3}$$

where H_b is the wave height at breaking, L_0 is the deep-water wave length, θ_b is the direction of wave propagation at breaking, m is the beach slope, t is time, T is wave period, d_{50} is the median grain size, L is the length of the structure, X is its distance to the coast, and X_{80} is the distance from shore within which 80% of the undisturbed littoral transport takes place. Therefore, X_{80} can be seen as a measure of the width of the surf zone.

ϕ_1 and ϕ_2 in (1) can be interpreted as being dimensionless parameters that describe the dependence of the morphological response on the magnitude of the sediment transport and the geometry of the structure, respectively.

In order to systematically investigate the dimensions of the detached breakwater that are required to obtain the desired response, tests in which the morphological response obtained by varying X/X_{80} and L/X_{80} in (3) while keeping constant the dimensionless parameters in (2) have to be defined. Therefore, 8 tests in which X/X_{80} and L/X_{80} were systematically varied while keeping the incident wave characteristics, the initial beach slope and the sediment properties unchanged were defined for the present analysis, as detailed in Table 1 below.

Table 1. Definition of test cases (X_{80} = 240m)

Test	X (m)	L (m)	X/X_{80}	L/X_{80}	L/X
KM1	120	312	0.50	1.30	2.60
KM2	240	312	1.00	1.30	1.30
KM3	360	312	1.50	1.30	0.87
KM4	480	312	2.00	1.30	0.65
KM5	600	312	2.50	1.30	0.52
KM6	360	192	1.50	0.80	0.53
KM7	360	432	1.50	1.80	1.20
KM8	360	552	1.50	2.30	1.53

Tests KM1 to KM5 were aimed to investigating the influence of the location of the structure with respect to the coast on the morphological response. Tests KM3, KM6, KM7 and KM8, in turn, were defined to investigate the influence of the length of the structure on this response.

In all the tests, irregular unidirectional waves were applied. The root-mean-square wave height H_{RMS}, peak wave period T_p and direction of wave propagation θ at a water depth of 10m were defined as equal to 2m, 8s and 10°, respectively. The initial beach slope m was kept as 1:50 in all tests, and a sediment with median grain size d_{50} = 0.25mm and geometrical standard deviation $\sigma_g = (d_{84}/d_{16})^{0.5} = 1.1$ was used over the whole model area. With this definition of parameters, a value of X_{80} = 240m was found.

Each morphological simulation test was carried out for a minimum period of nine days, after which the results were analysed. Even though it can be argued that the "final" morphological response of a natural beach to the local wave conditions will arise after a number of years, it must be kept in mind that this response will be mainly dictated by some significant (from a sediment-transport point of view) events. Normally, these events will have a limited persistence over an average year. Since the same (relatively rough) wave conditions were kept during the entire morphological simulation period reported here, it can be reasonably expected that the time scale required for the bathymetry to adapt itself to the incident waves will be much shorter in the model tests than in nature.

Presentation and discussion of results

Fig 1 shows the initial model bathymetry for tests KM3, KM5 and KM8. The area shown is 720m wide and 1800m long. The length of the structure is the same in tests KM3 and KM5, but the breakwater is located further away from the shore in KM5. On the other hand, the two breakwaters are located at the same position with respect to the coast in tests KM3 and KM8, but the length of the structure is almost double for the case of tests KM8, see table 1 for additional details.

Figs 2, 3 and 4 show the initial wave, current and sediment transport fields calculated over the same area as shown in Fig 1 for the three tests. Inspection of the figures shows how the dimension and location of the structure influence the nearshore hydrographic and transport conditions.

For example, it can be seen that placement of the structure further away from the coast for test KM5 permits more penetration of wave energy in the area behind the structure, cf. Fig 2. On the other hand, the sheltered area created by the structure along the coast is largest for this case (KM5), as shown by the extension of the recirculation area downstream of the breakwater in Fig 3. For test KM8, the penetration of wave energy behind the relatively long structure is so limited that two independent regions (from a sediment-transport point of view) exist in the vicinity of the tips of the structure, cf. Fig 4.

Fig 5 shows the bathymetry predicted by the morphological model after 10 days. All bed levels above –2m have been shown in black in order to facilitate interpretation of the results.

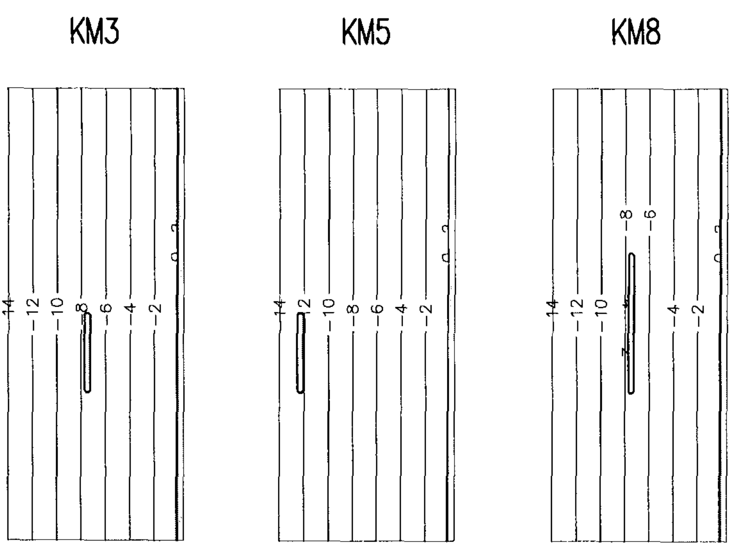

Figure 1. Initial model bathymetry

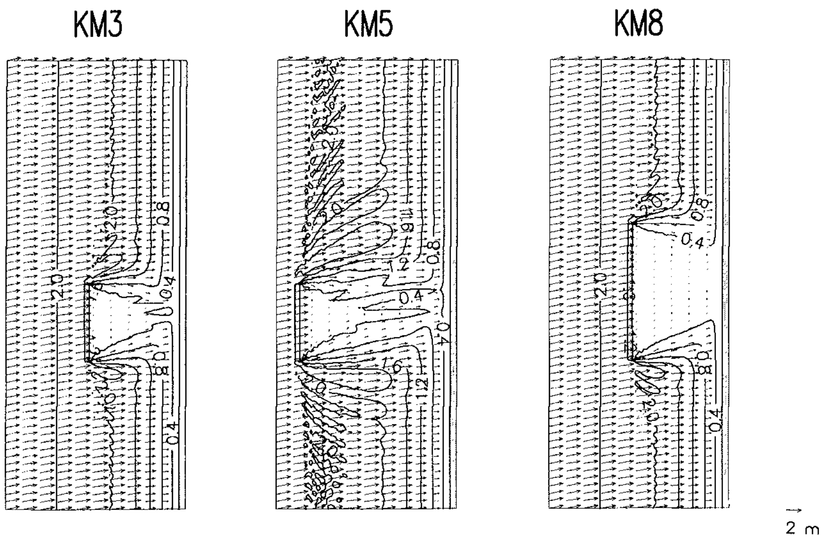

Figure 2. Initial wave fields

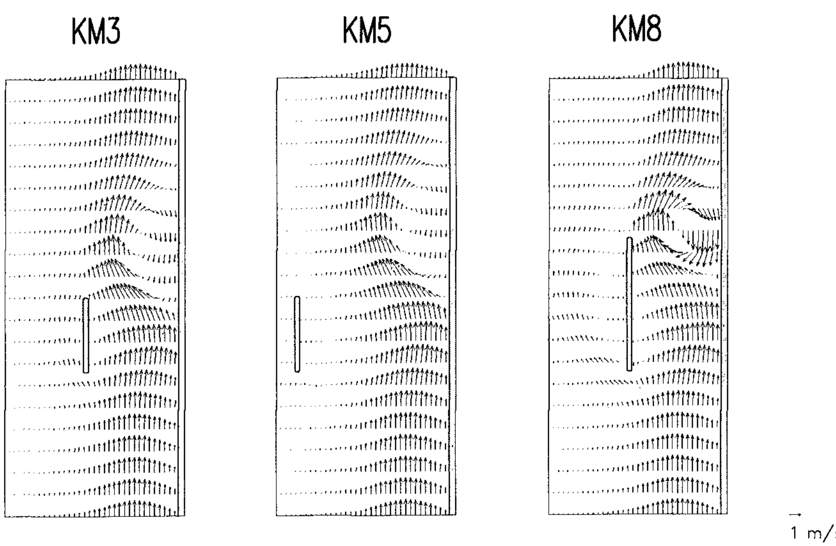

Figure 3. Initial wave-driven current fields

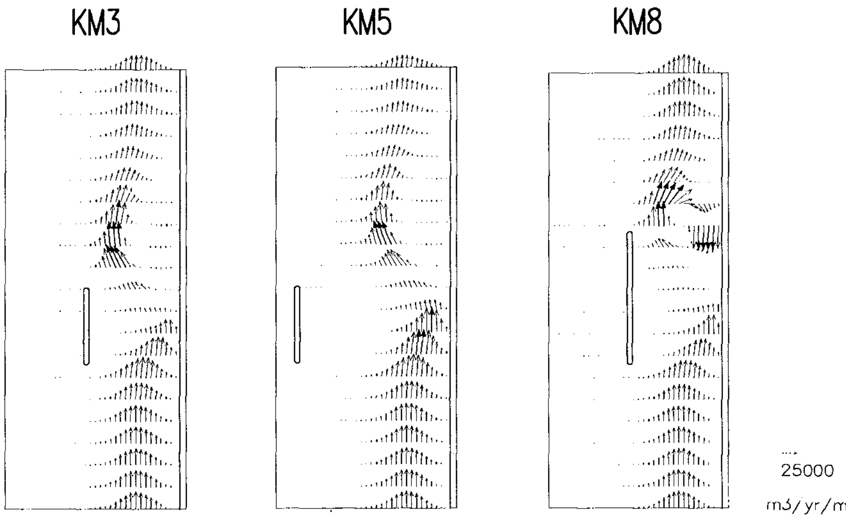

Figure 4. Initial sediment transport rates

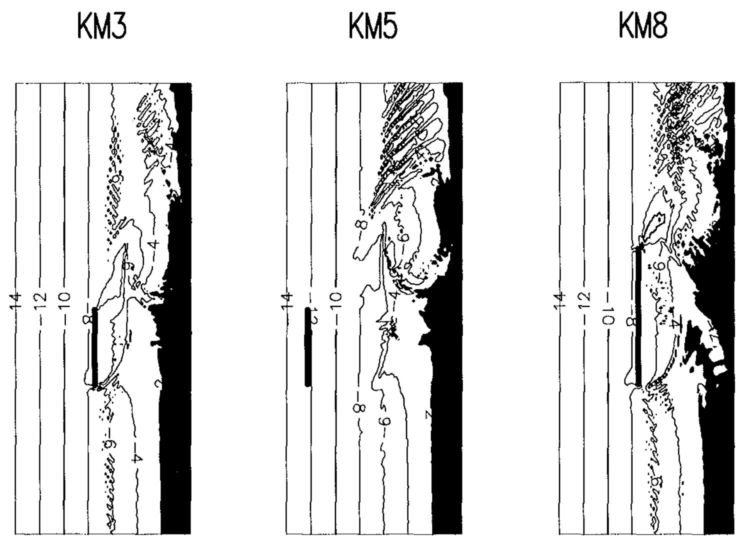

Figure 5. Predicted bathymetry after 10 days of simulation

The bathymetry predicted by the morphological modelling system at the end of each test was inspected and classified. The predicted planform was either classified as tombolo (for those cases in which the structure had become connected to the shore), or salient (if a widening of the beach had occurred without significant changes of the bathymetry beyond the shallower area) or salient/tombolo (if a significant salient not attached to the structure had developed at the end of the test).

The predicted response was compared to empirical formulas from the literature. The results of this comparison have been summarised in Table 2. It is observed that the predicted morphological response is generally in good agreement with the predictions from the empirical formulations.

The results obtained are summarised in graphical form in Fig 6 as a function of L/X_{80} and X/X_{80}. The empirical relationship $L/X = 1$, proposed among others by Herbich (1989) and Suh and Dalrymple (1987) to identify the occurrence of tombolo or not, has also been indicated. Points located above the line ($L/X > 1$) will correspond to tombolo formation, whereas points below the line ($L/X < 1$) will indicate salient formation, and points close to or right on the line will correspond to the case of unstable tombolo formation.

It is observed that the response predicted by the morphological modelling system is in good agreement with this empirical criterion.

Table 2. Comparison of Calculated Response to Empirical Formulas

Test	Herbich	Ahrens & Cox	Dally & Pope	Suh & Dalrymple	Mangor	Morphol. Modelling
KM1	Tombolo	Periodic tombolo	Tombolo	Tombolo		Tombolo
KM2	Tombolo	Well-developed salient		Tombolo	Salient	Tombolo
KM3	Salient	Subdued salient			Tombolo	Salient/ tombolo
KM4	Salient	Subdued salient	Salient		Salient	Salient
KM5	Salient	Limited accretion	Salient		Salient	Salient
KM6	Salient	Subdued salient	Salient		Salient	Salient
KM7	Tombolo	Well-developed salient		Tombolo	Tombolo	Tombolo
KM8	Tombolo	Well-developed salient	Tombolo	Tombolo	Tombolo	Tombolo

The coastal features observed behind three breakwaters located respectively on the West coast of Jutland, Denmark (stable tombolo), SW coast of Sri Lanka (unstable tombolo) and Sergipe (Brazil) have also been included in the figure. Again, good agreement between the model predictions and the observed response in the field is found.

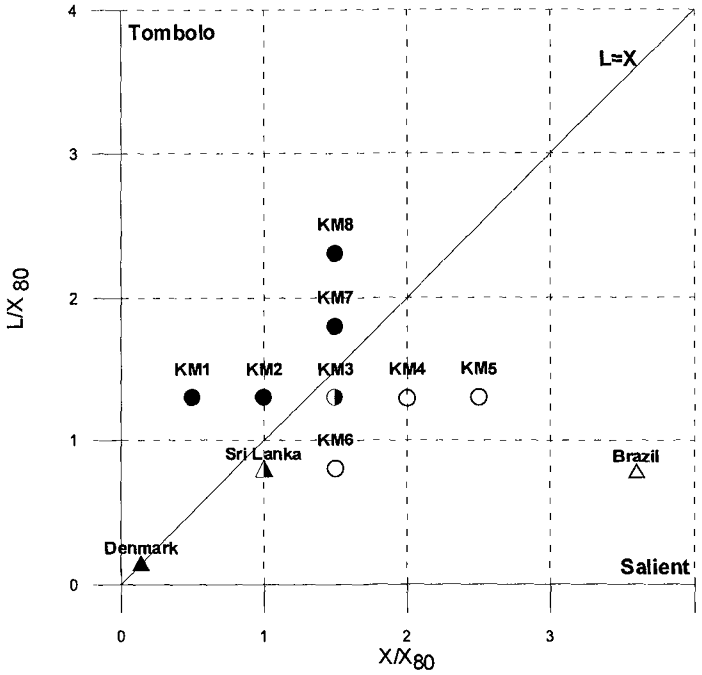

Figure 6. Calculated morphological response as a function of the length and location of the detached breakwater. Triangles: field data. Circles: model results. Open symbols: salient. Filled symbols: tombolo.

The dependence of the modelling results on the dimensions and the position of the breakwater were investigated through the total volume of sediment deposited on the initial bathymetry after 9 days of simulation.

The results have been plotted in Fig. 7 as a function of the distance from the coast to the structure for breakwaters of constant length (tests KM1 to KM5) and in Fig. 8 as a function of the length of the breakwater for breakwaters with constant distance to the coast (tests KM3, KM6, KM7 and KM8). The labels close to the symbols in both figures indicate the corresponding ratio L/X for the breakwater.

Fig 7 shows that for a detached breakwater of given length, there is an optimal location from the point of view of the amount of sediment that the structure will trap. In the extremes, a breakwater located very close to the coast will trap small amounts of sediment, as it will only marginally interfere with the surf zone.

On the other hand, a breakwater located too far away from the coast will also trap moderate amounts of sediment, since there will be space enough behind the structure for wave energy to penetrate and for the waves to reform before reaching the outer edge of the surf zone.

Fig 8 shows that for a breakwater located at a certain distance from the shore, a limiting length exists beyond which the amount of sediment trapped by the structure will not increase with its length. This is due to the fact that no penetration at all of wave energy behind the structure is possible due to its length, and therefore the transport processes at both ends of the structure occur independently of each other.

Figs 7 and 8 can be used in combination to optimise the design of a shore-parallel breakwater from the point of view of the desired morphological response. If thc length of the breakwater has been defined beforehand, or if it is restricted by external requirements, then Fig 7 can be used to determine the location of the structure that will yield the maximum deposited volume (if desired). The morphological modelling system will in turn predict the type of planform that will be created behind the structure.

If the position of the breakwater with respect to the coast is fixed, then Fig. 8 can be used to optimise its length, and the morphological modelling results (or, altcrnatively, Fig 6) to verify the type of morphological feature that will be generated.

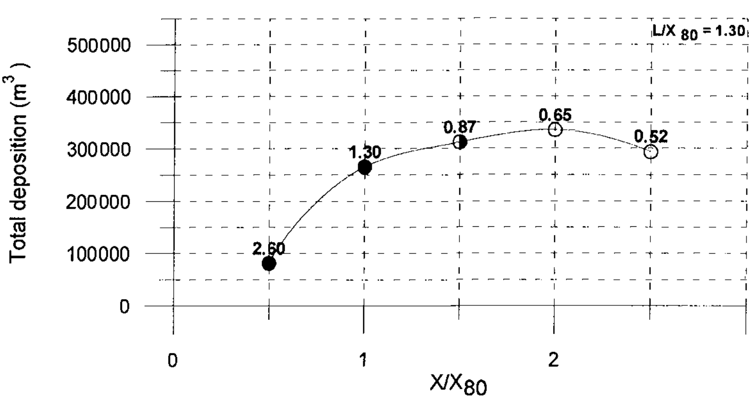

Figure 7 Influence of distance to coast on the amount of sediment deposited on the initial bathymetry. All breakwaters have L = 312m. Figures on the plot correspond to values of L/X. Symbols as in Fig 6.

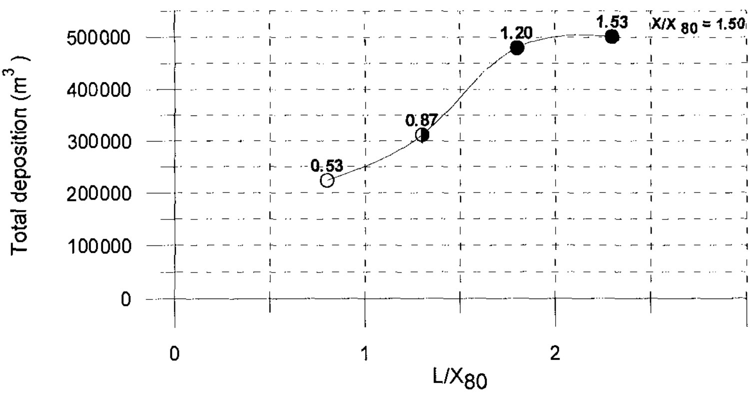

Figure 8 Influence of structure length on the amount of sediment deposited on the initial bathymetry. All breakwaters have X = 360m. Figures on the plot correspond to values of L/X. Symbols as in Fig 6.

It is important to keep in mind that Figs 7 and 8 are not general design curves, but have been created for a particular wave climate and beach profile. Application of the morphological modelling system as described in the previous sections to the particular hydrographic and sedimentological conditions found at a given study site will therefore allow the optimisation of the dimensions of shore-parallel breakwaters from the point of view of the associated morphological response.

Currents generated in the vicinity of shore-parallel breakwaters

Shore-parallel breakwaters are frequently used as coastal structures in connection with recreational beaches, either to stabilise the coastline or to provide swimming areas that are sheltered from the incoming waves.

Since complex current patterns are generated in the vicinity of detached breakwaters, the sheltered areas may prove hazardous for inexperienced swimmers, who will be attracted to the apparently calm areas where they may be trapped by the current and be dragged offshore.

In order to quantify the magnitude of these currents, the maximum current speed predicted by the hydrodynamic model on the initial bathymetry for each of the eight tests has been listed in Table 3 below. These strong currents always take place shoreward or close to the tips of the breakwater.

The figures in Table 3 may be compared to the maximum value of 1.33 m/s attained by the wave-driven current along the open stretch upstream of the breakwater.

Table 3. Magnitude of the currents in the vicinity of the breakwater

Test	Max. speed on initial bathymetry
KM1	1.50
KM2	1.70
KM3	1.68
KM4	1.66
KM5	1.63
KM6	1.53
KM7	1.95
KM8	1.89

It can be seen that the currents generated by the presence of the shore-parallel breakwater can be up to 40% stronger than the maximum value of the wave-driven current.

Conclusions

The application of the coastal morphological modelling system to the design of shore-parallel breakwaters allows determining the optimal geometry of an isolated structure for given wave conditions and characteristics of the beach profile and the bed material.

The morphological response predicted by the modelling system is in good agreement with observations from the field and the guidelines provided by commonly used empirical formulas.

Even though the results obtained indicate that depth-integrated currents are the dominating mechanism from the point of view of the morphological response, there is a number of additional effects, the significance of which is not fully understood yet, and should therefore be the subject of future investigations. Among them, the vertical structure of the wave-driven currents and the suspended sediment transport, bed-slope and space-lag (non-equilibrium suspended load transport) effects on sediment transport may be mentioned.

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