5 Application to Coastal Situations – Detached Breakwater

5.1 Introduction

Offshore breakwaters have been used in the past as a coast protection measure; to stabilize a section of coast, to limit sand erosion, or to provide calm waters for recreational activities (King et al., 2000; Ming and Chiew, 2000; Alsina et al., 2003). The design of breakwaters requires, amongst other things, the accurate prediction of equilibrium morphologies so that the final shoreline can be determined and fill volumes calculated. Currently, the evolution of coastal morphologies is modelled using traditional process-based computer models (e.g. Nicholson et al., 1997; Zyserman and Johnson, 2002), where wave, current, sediment transport and sediment balance modules are linked together in a time-stepping process. These modules are applied in sequence and time stepping continues until a stable or equilibrium morphology is formed. These types of models may have a number of possible limitations. For example, small errors may be amplified over the time-stepping process, and starting conditions impart a large influence on the predicted morphology (de Vriend et al., 1993, Hanson et al., 2003). Another issue with the process-based models is that they must include realistic sediment transport routines. Sediment transport modules are utilised to update the bed, distributing sediment that may have moved over the modelled time-step. In this Chapter, a similar type of modelling method to that used in Chapter Four is outlined, where the processes are not modelled explicitly, and where there is no time stepping. Rather an iterative approach is set up where a solution is sought using an optimisation procedure. The approach is new to coastal problems, but has been used in the past by river modellers (see Chapter Two).

Global search methods have been used to calibrate parameters of sediment transport, current and wave models, as was discussed in Chapter Two, Section 2.3.1 (Davidson et al., 2000; Medina, 2001; Knaapen and Hulscher, 2003; Kizhisseri et al., 2005; Ruessink, 2005b). This thesis takes a different approach, which to the author's knowledge has not been applied to a surf zone morphological problem before. Optimisation is utilised, not to calibrate parameters, but to generate and search through an initially random set of coastal morphologies to determine a final solution that is close to the equilibrium configuration.

The case study to which the optimisation-based modelling method is applied in this Chapter, considers a shore parallel, surface piercing, detached breakwater. It is placed on a stretch of shoreline where the morphology is initially at equilibrium. Regular waves attack the beach, forming a salient or tombolo type morphology at equilibrium as shown in Figure 5.1.

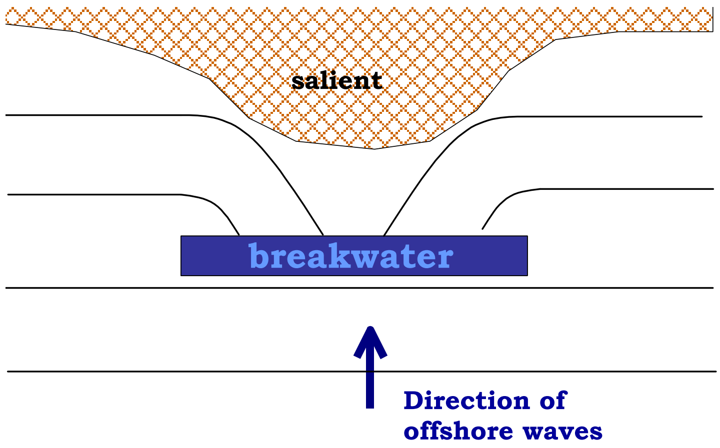

Figure 5.1 Idealised salient equilibrium morphology associated with a shore-parallel detached breakwater.

The system studied in this Chapter is more complex than the river environments in the previous Chapter, where fixed boundaries and unidirectional flow allowed for energy dissipation calculations throughout the system to be made. Optimisation methods were then used to determine which erosional channel formed a system with minimum energy dissipation. In the breakwater situation, at equilibrium, there is minimal sediment transport as the system has formed a stable equilibrium morphology, typically a salient or tombolo. The same optimisation method is used in this Chapter as the previous one, but with an objective function based on minimum sediment transport. This approach avoids the need to step through time and diminishes the reliance of the predicted morphology on accurate and detailed initial conditions. It is a method that considers a system moving towards an equilibrium morphology, and is able to predict that equilibrium morphology directly.

A laboratory study was undertaken to observe the stable morphologies that form due to the insertion of a shore-parallel breakwater along a stretch of coastline. A comparison of the morphologies observed at equilibrium before and after the breakwater placement is shown in Figure 5.2. This Figure shows the bending of the SWL to form a salient in the lee of the breakwater, in contrast to the initial position of the SWL parallel to the shoreline. A description of the laboratory method and results is documented in Appendix E.

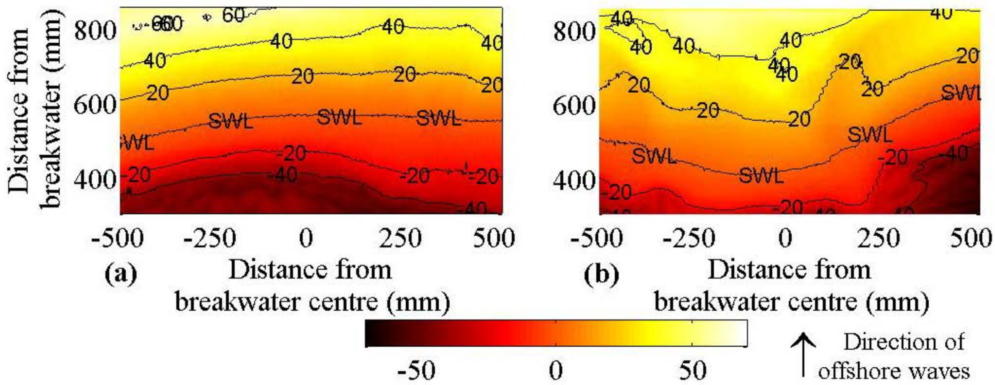

Figure 5.2 Comparison of equilibrium morphologies observed (a) before and (b) after shore-parallel breakwater insertion in a laboratory experiment. The shore-parallel detached breakwater was located at (0,0), with a width of 585mm.

The following Sections describe the model, give results of sensitivity analyses and outline discussions and conclusions.

5.2 Model Description

The model that has been developed to predict equilibrium morphologies associated with detached breakwaters utilises standard wave, current and sediment transport calculating modules. The wave model used a hyperbolic approximation to the Mild Slope Equation originally derived by Copeland (1985). The current model solved the two-dimensional depth-averaged flow field based on a solution of the Navier-Stokes equations. The sediment transport model employed a modified Ackers-White formula, as described by Sleath (1984). A full description of the modules can be found in Walker et al. (1991). In the present work the modules have been configured to accommodate an optimisation routine which allowed a comparison of morphological snapshots based on an objective function, to determine which was closer to a stable equilibrium morphology.

The objective function was utilised in the optimisation modules. These minimised the objective function either by a genetic algorithm (GA) or simulated annealing (SA). Both GAs and SAs are global optimisation routines and have been discussed in detail in the previous Chapter, Section 4.2.

Initially, the GA generated a population of 50 random morphologies, where the elevation of each morphological grid varied randomly above or below an initial beach slope. A typical starting morphology is shown in Figure 5.3. The initial beach slope was taken as being at equilibrium before the positioning of the shore parallel breakwater. The initial morphologies contained random elevations, with as much as 7.5m in height difference between grid cells if the initial limits for random elevation generation were fixed at 4m deposition and 3m erosion for the entire area.

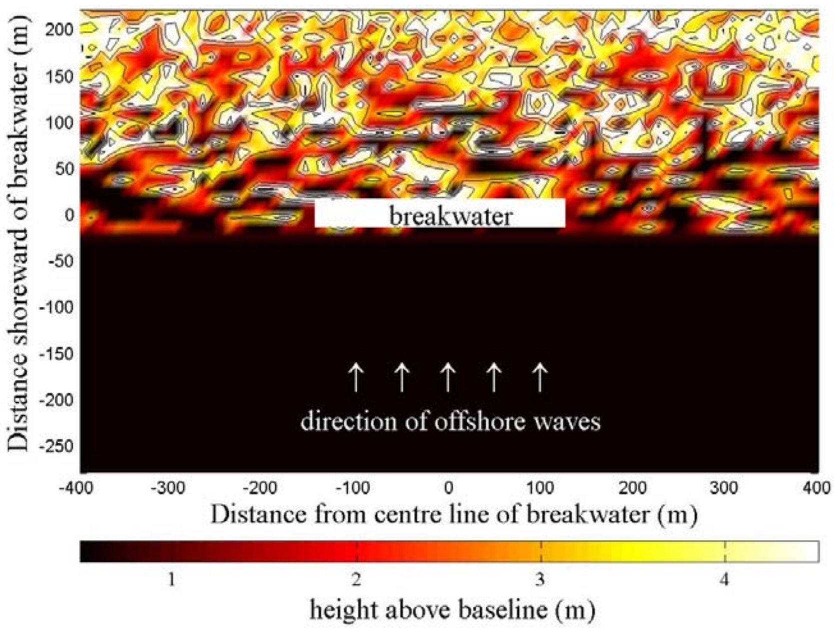

Figure 5.3 Typical randomly generated starting morphology.

To help the model avoid improbable solutions and reduce computation time involved with finding solutions to infeasible morphologies, variable limits were used. Variable limits were related back to the water depth, with the elevation allowable for each decision variable being a percentage of the water depth. In general 60% of the water depth for erosion areas and 30% of the water depth for deposition areas with respect to the initial beach slope, gave the best results. A sensitivity analysis of this result is discussed in Section 5.4.2. The model was quickly able to modify the initial random morphology, pinpointing areas of deposition and erosion.

The area over which random morphologies were defined covered the area where the breakwater was expected to have an effect on the local beach slope. This was determined based on modelling of similar situations by Nicholson et al. (1997) and Zyserman and Johnson (2002). The model solution encompassed an area greater than this, with fixed morphology at the extremities taken as the initial equilibrium beach slope. This is shown in Figure 5.4. The edges where the random and specified morphologies met helped to direct the solution to a plausible morphology. This is because a difference in elevation at this interface leads to a large predicted rate of sediment transport and therefore a poor value for the objective function. The interface helped to keep the random morphologies in check, so that the morphology only altered if it decreased the overall sediment transport, without creating an isolated local effect due to high variation in elevation between it and its neighbour.

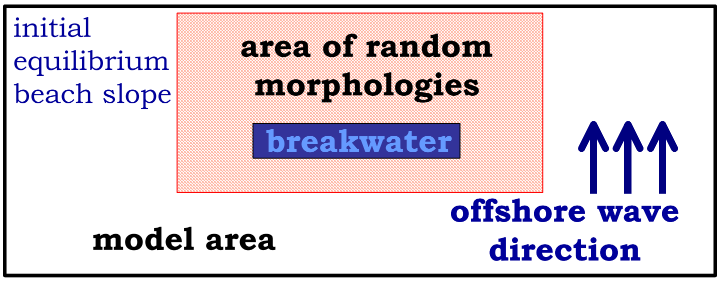

Figure 5.4 Description of random elevation prediction areas.

At each iteration a new morphology was randomly formed and the wave field was solved over the total grid. The output from the wave model included the radiation stresses, which were input into the Navier-Stokes current model. The wave height from the wave model and the current vectors from the current model were used in the sediment transport model to predict the total sediment transport over the entire grid. From the results of this an objective function value was calculated. The objective function was based on the total sum of the sediment transport throughout the modelled system. This is shown in Eq. (5.1).

$$OF = \sum_{all\ i,j} \left| q_{ij} \right| \quad (5.1)$$

where OF is the overall objective function value (m^3s^{-1}); and

q_{ij} is the sediment transport at each grid point where the current is calculated, based on the modified Ackers-White formula (Q_s) which accounts for both currents and waves (Sleath, 1984) (see Eqs. 5.2-5.9) (m^3s^{-1}).

$$\frac{Q_s}{\overline{U}d} = \frac{D_{35}}{d}\left(\frac{\overline{U}}{\overline{u}_*}\right)^n C_1\left(\frac{F_{wc}-A}{A}\right)^m \quad (5.2)$$

$$F_{wc} = \left(\frac{\overline{u}_{*wc}}{\overline{u}_*}\right)^n F \quad (5.3)$$

$$\frac{\overline{u}_{*wc}}{\overline{u}_*} = \left(1 + 8.28 f_w \log_{10}^2\left(\frac{12d}{k_s}\right)\frac{U_\infty^2}{\overline{U}^2}\right)^{1/2} \quad (5.4)$$

$$F = \left(\frac{\overline{U}}{2.46\ln\left(\frac{10d}{D_{35}}\right)}\right)^{1-n} \frac{\overline{u}_*^n}{\left(\frac{\rho_s-\rho}{\rho}gD_{35}\right)^{1/2}} \quad (5.5)$$

$$D_* = \left(\frac{\rho_s - \rho}{\rho} \frac{g}{v^2} \right)^{1/3} D_{35} \qquad (5.6)$$

$$\text{for } D_* > 60 \quad \begin{aligned} n &= 0 \\ A &= 0.17 \\ m &= 1.5 \\ C_1 &= 0.025 \end{aligned} \qquad (5.7)$$

$$\text{for } 1 < D_* \le 60 \quad \begin{aligned} n &= 1 - 0.243 \ln D_* \\ A &= \frac{0.23}{D_*^{1/2}} + 0.14 && \text{if } \frac{U_\infty}{\bar{u}_*} \le 10 \\ A &= 2.29 \left[\frac{\rho f_w}{(\rho_s - \rho) g} \right]^{1/2} \frac{T^{0.043}}{D^{0.12}} && \text{if } \frac{U_\infty}{\bar{u}_*} > 10 \\ m &= \frac{9.66}{D_*} + 1.34 \\ C_1 &= \exp\left[2.86 \ln D_* - 0.434 (\ln D_*)^2 - 8.13 \right] \end{aligned} \qquad (5.8)$$

$$f_w = \frac{2\hat{\tau}_0}{\rho U_\infty^2} \qquad (5.9)$$

where d is the mean depth of water (m);

D is the median grain size of the sediment (m);

D_{35} is the grain size exceeded by 65% by weight of a sample of sediment;

f_w is the wave friction factor;

g is acceleration due to gravity (ms^{-2});

k_s is the roughness length of the bed;

Q_s is the time-mean volumetric transport rate of sediment (m^{3}s^{-1});

T is the period of oscillation (s);

$\bar{u}_*$ is the time-mean value of u$_*$ (ms^{-1});

$\overline{U}$ is the mean value of u over a vertical (ms^{-1});

U_∞ is the amplitude of u$_0$ (ms^{-1});

v is the kinematic viscosity;

ρ is the fluid density;

ρ_s is the density of sediment;

$\hat{\tau}_0$ is the amplitude of ; and

τ_0 is the shear stress on the bed.

An angle of repose penalty was not required in the calculation of the objective function as the distance between grid cell centre points, relative to the maximum elevation difference between each point was less than the maximum angle of repose, even in extreme cases.

In contrast to the previous Chapter, where a combined GA-SA optimisation approach was used to find equilibrium morphologies, a new method was developed to handle an extremely large number of decision variables. In the lagoon case study discussed in Chapter Four, Section 4.3, the optimisation modules had to solve for 265 decision variables. In the problems discussed in this Chapter, if every grid point were to be considered as a decision variable, then over 2160 decision variables would need to be solved for. This dramatically increases computation time as the solution space becomes very large, and the optimisation techniques can become stuck in local minima more easily, particularly if the solution space is relatively flat near the global minimum. Franconi and Jennison (1997) noted this problem when they optimised a large number of decision variables. To get around this problem associated with large numbers of decision variables, the morphological grid size used was larger than that of the current or wave modules. This reduced the number of decision variables to a value similar to the lagoon case study analysed in Chapter Four. There was a trade off however, between morphological definition and computation time. If the morphological grid size became too large, the computation time decreased, as the solution space it must search was smaller due to the fewer number of decision variables. The fitness values were worse however, as the decision variable value covered a large area. If deposition occurred in the lee of the breakwater, it could spill over to either side of the breakwater due to the coarseness of the morphological grid.

Sensitivity analyses were undertaken, as discussed in Section 5.4, and in general, the transverse grid size, between the beach and the breakwater was kept at the same width as the current module (10 metres). This is because it was assumed that the greater variability in morphology would occur here, as inferred from a number of laboratory studies, detailed in Appendix E. The morphological grid size in the longitudinal direction, parallel to the breakwater was altered. It was kept either constant, if a GA-SA optimisation module was used, or reduced after a set number of generations if a top-down model, the new method introduced in this Chapter, was utilised. In the sensitivity section of this Chapter (Section 5.4), the two optimisation methods are compared.

The top-down optimisation method involved the use of a GA, but, after a specified number of generations, the morphological grid size was reduced. This allowed the model to pinpoint the general areas where deposition and erosion should occur initially, allowing these areas to be refined and better defined as the optimisation progressed. This increased the efficiency of the model and lessened the possibility that the number of random variables would overwhelm the model and stagnate it prematurely. A flow chart showing the method utilised by the top-down model is shown in Figure 5.5.

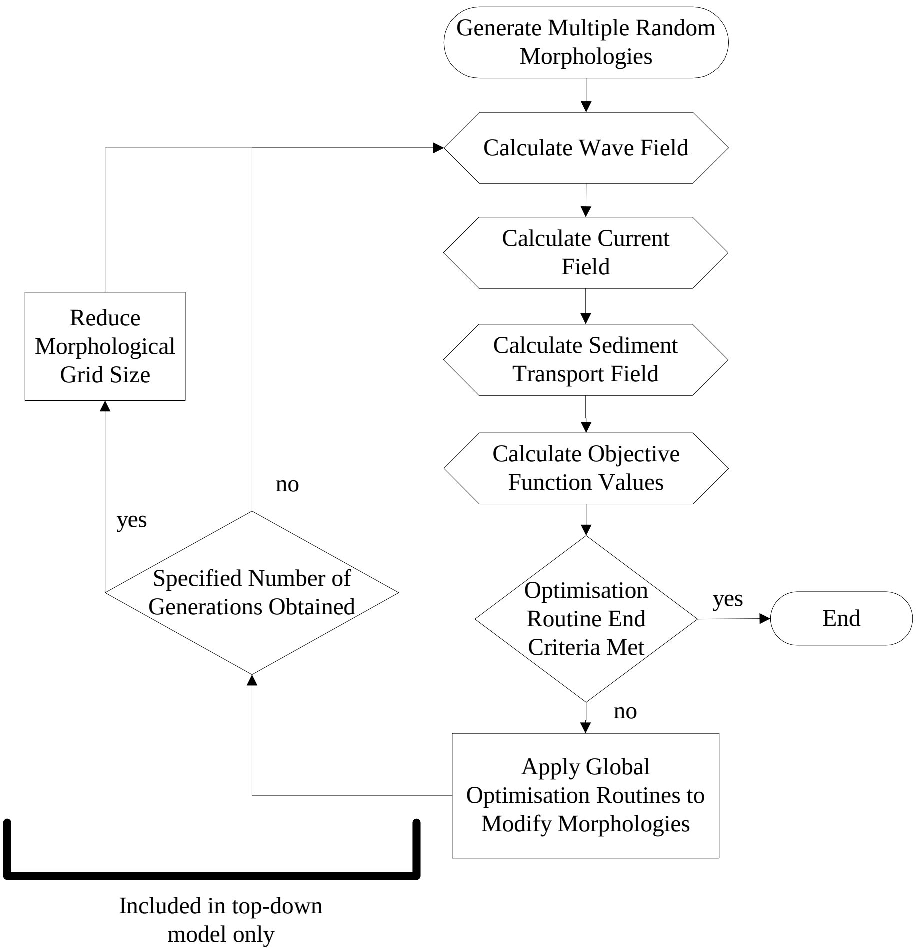

Figure 5.5 General methodology of top-down model.

5.3 Case Study Description

As a test case, the offshore breakwater modelled by Nicholson et al. (1997) was set up, with a 300m wide breakwater placed 220m offshore, as pictured in Figure 5.6. The system was subjected to regular waves with a period of 8s and height of 2m. The direction of the offshore waves was perpendicular to the breakwater. The initial beach slope was 0.02m/m. The current module used a grid size of 10m and the wave module a grid size of 5m. The actual modelled area was 1.5km by 0.5km, with random morphologies generated in an area 0.9km by 0.25km.

Examples of equilibrium morphologies associated with shore-parallel detached breakwaters can be seen in Figure 5.7 and Figure 5.8. Only half of the system, from the centre point of the breakwater is shown in these figures. These steady-state morphologies were obtained using different 2DH process-based models (Danish Hydraulic Institute model (DHI) and Service Technique Central des Ports Maritimes et des Voies Navigables model (STC)). They show that in a similar field set-up it is likely that a salient or submerged tombolo will form at equilibrium.

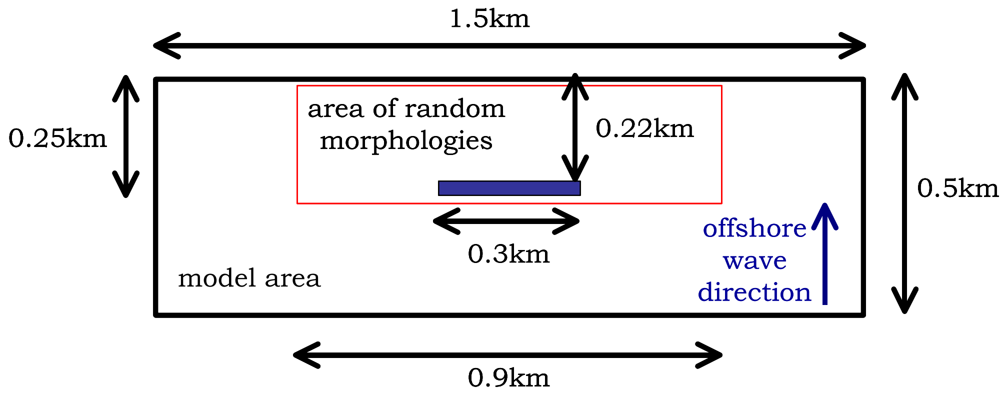

Figure 5.6 Breakwater set-up after Nicholson et al. (1997).

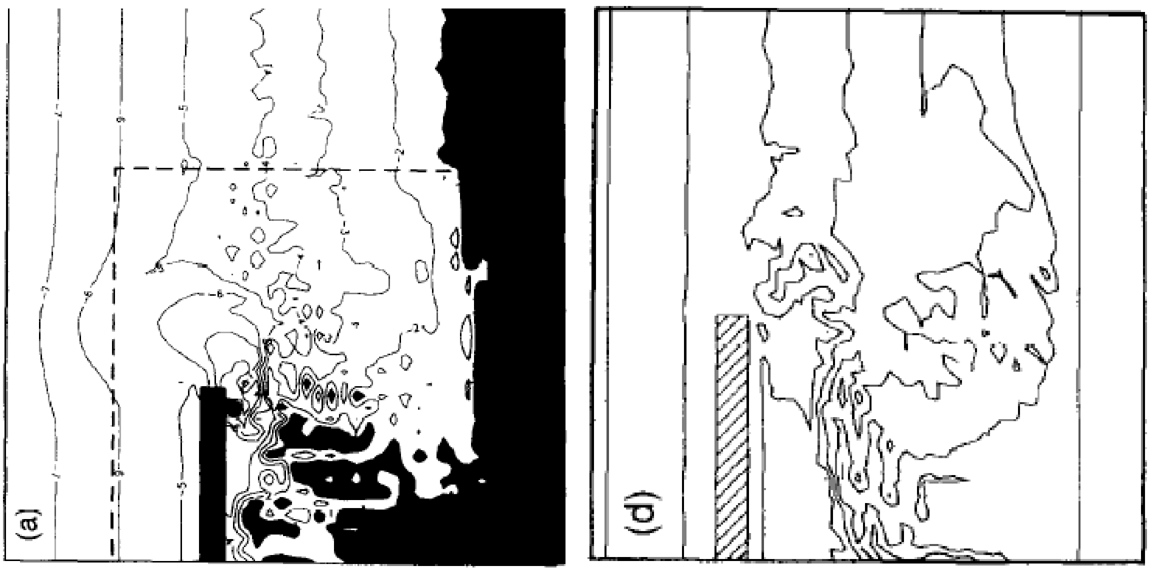

Figure 5.7 Examples of steady-state morphologies obtained using different 2DH process-based models – (a) DHI and (d) STC (after Nicholson et al., 1997).

The morphology shown in Figure 5.8 is much smoother than the morphologies in Figure 5.7 due to the different descriptions of the wave, current and sediment trasport modules. Although the morphologies in Figure 5.7 are fragmented, clear areas of deposition in the lee of the breakwater exist.

The following Section details the results obtained using an optimisation-based model in a similar case study situation. Sensitivity analyses are discussed. All morphological grid cells had a cross-shore size of 10m, consistent with the current module grid size. The longshore direction however, was modelled using a variety of morphological grid sizes. The use of a coarse, fine or top-down variable morphological grid size is discussed as well as the variation of the limits within which the random morphologies were defined.

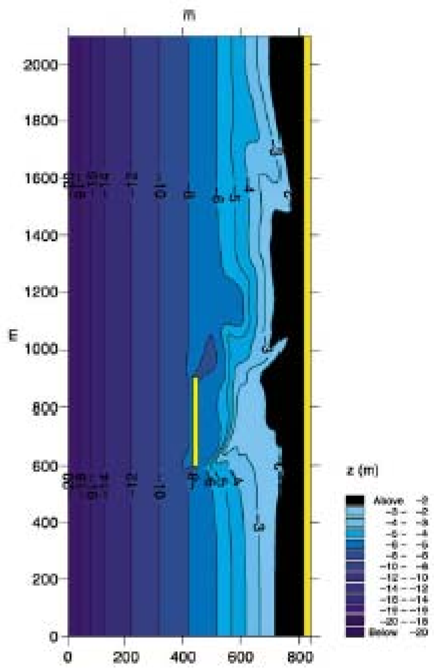

Figure 5.8 Morphology associated with a detached breakwater after 14 days using a 2DH model (after Zyserman and Johnson, 2002).

5.4 Breakwater Model Results and Sensitivity Analyses

A top-down model was used to make the best equilibrium morphological predictions, as it was found to be superior to a GA-SA model. The top-down model was able to find a rough morphology using a smaller number of decision variables. It was then able to refine the morphology by introducing more variables, without the optimisation method becoming inefficient due to an initial overly large solution space.

The best morphology was obtained using variable limits of 60% of the water depth in deposition and 30% in erosion. The top-down model used grid sizes of 80m, 40m and 20m, with the grid size reduced after 100 and 200 generations respectively. Discussions on the use of variable or fixed limits as well as top-down or standard GA-SA models are given in Sections 5.4.2 and 5.4.3

respectively. The resultant morphology can be seen in Figure 5.9. A salient has begun to form in the lee of the breakwater. Due to the relaxed limits that allow the elevation difference between two grid cells to be as much as 90% of the water depth, there is some fragmentation, and pockets of erosion and deposition throughout the system, but overall deposition has occurred in the lee of the breakwater.

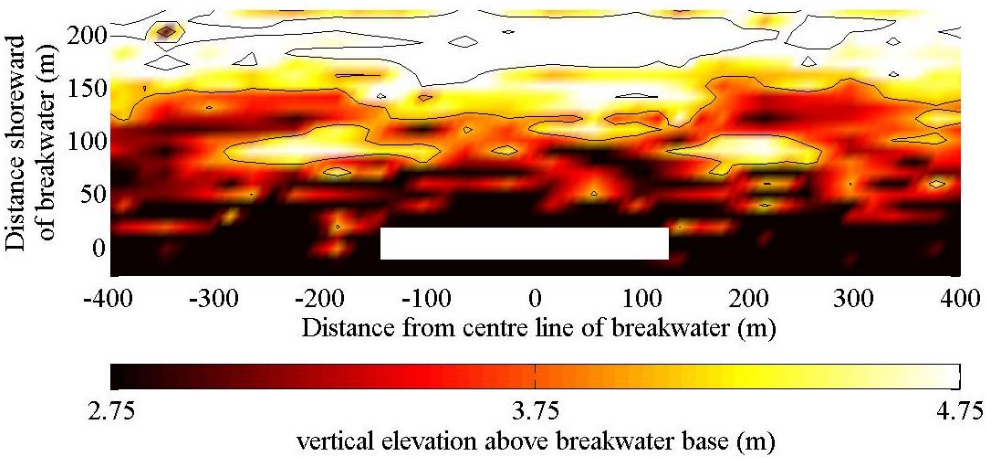

Figure 5.9 The resultant morphology after GA optimisation using a top-down model and variable elevation limits of 60% of the water depth in deposition and 30% in erosion.

This result shows similarities to those obtained as part of the Nicholson et al. (1997) study. A salient has formed, but there is still fragmentation with pockets of erosion and deposition spread across the modelled area. The optimisation-based model result does not extend as far offshore as the traditional model result.

There are some limitations to the optimisation-based method. In a similar way to the limitations observed in Chapter Four, the objective function definition controls the end morphology. In Chapter Four, Section 4.5, the objective function was designed to predict erosional channels and was unable to correctly predict the equilibrium shape of the deposition mound in the laboratory lagoon experiments. In the coastal problem, deposition is predicted in the lee of the breakwater, but only in a controlled shape where it affects the sediment transport. In deep-water areas, small pockets of erosion and deposition do not affect the sediment transport as they are below the threshold for transport, so they can occur without the optimisation-based model having a need to remove them.

Similarly, pockets of deposition occur in the centre of the two current circulation cells in the lee of the breakwater, as they do not affect sediment transport. If irregular waves were used as in a field situation, it is likely these mounds would be smoothed and become dissipated.

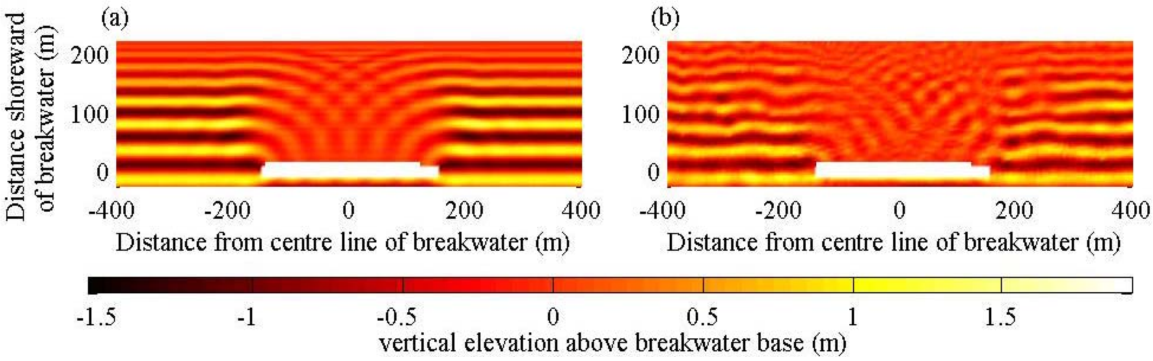

Figure 5.10 Initial and final wave pattern for (a) a sloping beach and (b) the morphology shown in Figure 5.9.

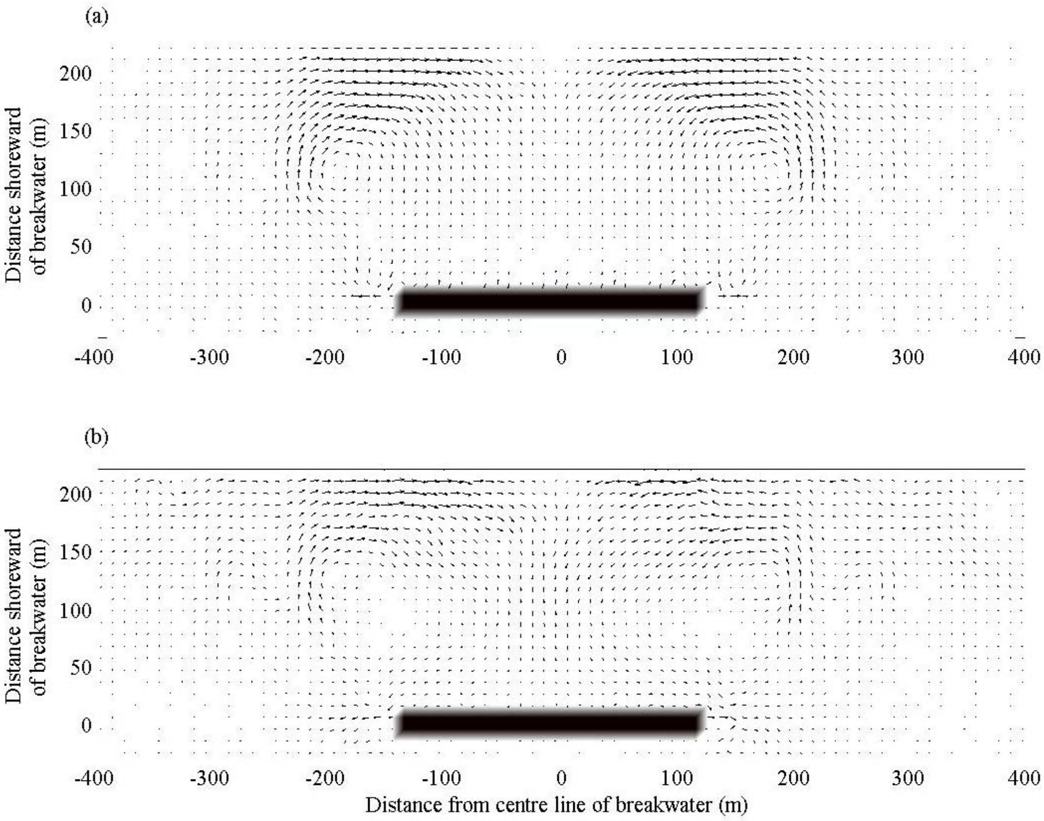

Figure 5.11 Initial and final velocity pattern for (a) a sloping beach and (b) the morphology shown in Figure 5.9.

In a similar way to the differing results of the Nicholson et al. (1997) and Zyserman and Johnson (2002) studies, the optimisation model is limited by the hydraulic calculations of the wave and current models. The initial and final wave and velocity states are shown in Figure 5.10 and Figure 5.11. It can be seen that they have been modified by the end morphology. Their accuracy in situations with large elevation differences is lessened, adding to the limitations of the method. However, as with all models, the use of more detailed hydrodynamics and sediment transport modules may improve results.

A number of sensitivity analyses were undertaken to test the limits and robustness of the optimisation method, and the effect different parameters had on its ability to predict morphologies.

5.4.1 Sensitivity to Initial Random Morphologies

A number of different runs were compared, where different seeds were used to generate the initial random morphologies. This tested the robustness of the method, in that the optimisation mechanism was able to determine morphologies with minimum objective function values that did not inherit the initial random morphologies they were seeded with. A comparison of four resultant morphologies using a top-down model with variable limits, where different initial populations of randomly generated morphologies were utilised is shown in Figure 5.12. The morphology in (a) uses the same random number seed as the remainder of the runs in this Chapter, while (b), (c) and (d) use different random number seeds.

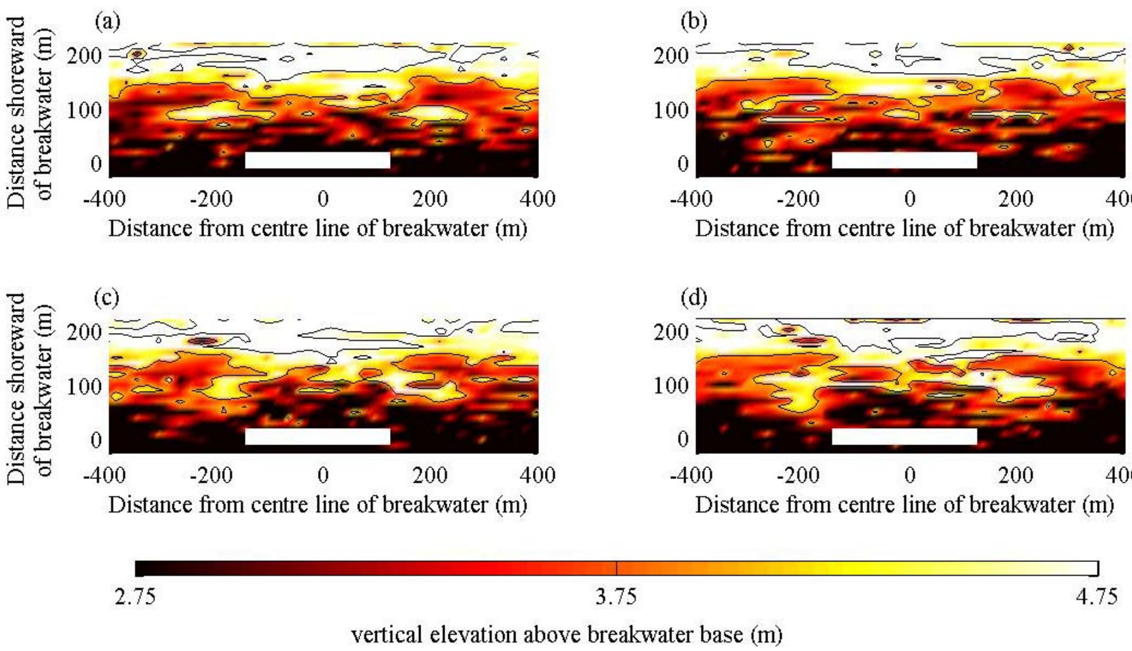

Figure 5.12 Comparison of equilibrium morphologies obtained using a top-down model with variable limits and different seeds to generate the initial populations of random morphologies which the model then optimises.

A comparison of these morphologies shows, that while the detail of each is different, the overall deposition mounds are of a similar shape in a similar position. This shows that the optimisation method is robust as it is able to predict similar equilibrium morphologies from completely different random starting morphology sets. All morphologies show similar characteristics to Figure 5.12 (a). They all predict deposition in the lee of the breakwater and all show signs of the limitations of the method, with fragmentation in deeper water and deposition in the centres of the current circulation cells.

A comparison of the objective function paths of the runs with different random starting morphologies is shown in Figure 5.13. Each path reached a similar objective function value. However, as can be seen in run (a), a slightly lower objective function value of 0.0066 was obtained when compared to run (b) which obtained a minimum value of 0.0083. This can be explained by a comparison of their morphologies shown in Figure 5.12 (a) and (b), where (a) developed a slightly fuller salient formation in the lee of the breakwater. The minimum objective function value obtained in run (d) was slightly lower than that obtained in run (a). A comparison of the two morphologies in Figure 5.12 (a) and (d) shows that in run (d), the salient formation extended a greater distance towards the breakwater which contributed to a reduction in sediment transport and hence a lowering of the objective function value from 0.0066 to 0.006.

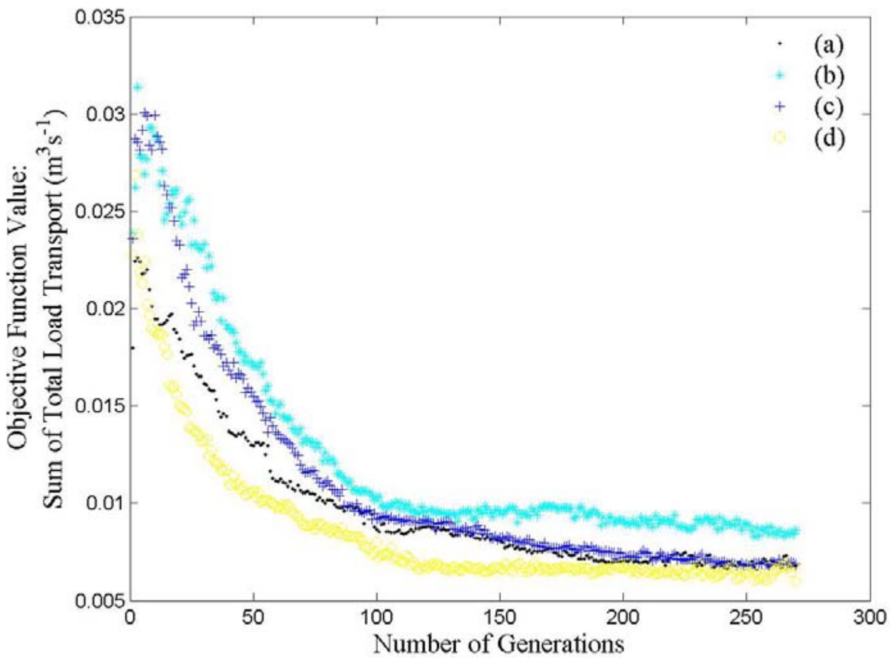

Figure 5.13 Comparison of objective function paths for different random starting morphologies, where (a), (b), (c) and (d) correspond to the morphologies shown in Figure 5.12.

5.4.2 Inclusion of Variable Limits with Water Depth

A number of different variable limit scenarios were trialled and the resultant morphologies compared to those obtained using fixed limits. Variable limits define the random elevations originally prescribed for each decision variable over the analysed morphology relative to the water depth. This assumes that the morphology of the beach is equivalent to the equilibrium beach slope before the positioning of the breakwater parallel to the shoreline. This is portrayed in Figure 5.14.

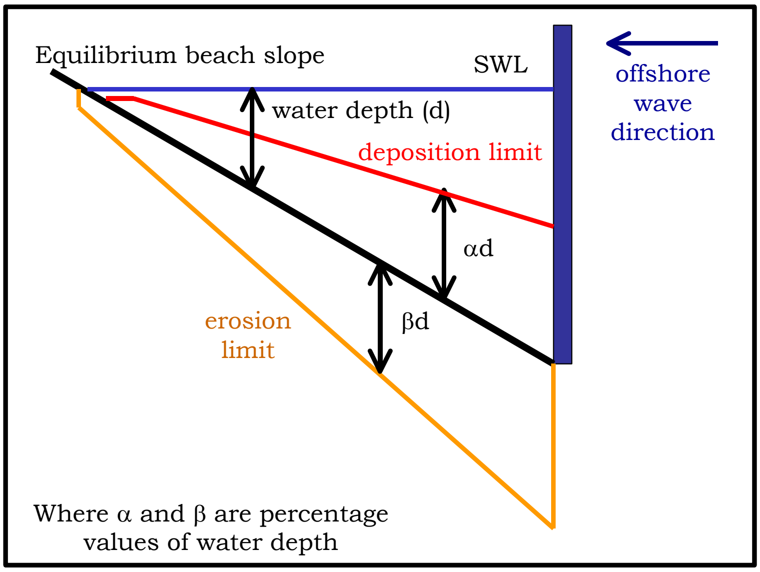

Figure 5.14 Definition of variable limits.

The use of variable limits was designed to predict an equilibrium morphology that was smoother than that obtained with fixed limits, as the number of possible solutions for elevations in shallower water was reduced. This in turn helped to reduce computational time and increase optimisation efficiency, as the solution space was reduced so the optimisation module did not have to search as many possible elevation combinations. The hydrodynamic model was unable to perform calculations over a system with changing wet and dry areas. Therefore, when fixed limits were utilised, a cut-off was prescribed, where the water depth must be at least 20cm. This was also adopted in the variable limits scenario. In the fixed limit study, in deep water, the elevations chosen could be anywhere from the maximum elevation difference below the initial equilibrium slope, to the maximum elevation difference above the initial equilibrium slope (see Figure 5.15). In the variable limits study, the elevation could only be a percentage of the water depth. The use of variable limits introduced less variability in shallow water areas and greater variability in deeper water areas.

A number of different variable limit percentage of water depth for erosion and deposition were trialled and contrast to each other. The results of using 45% water depth for erosion and 20% water depth for deposition are shown in Figure 5.16 (a). This morphology was compared to that obtained using variable limits of 60% water depth for erosion and 30% water depth for deposition as shown in Figure 5.16 (b) and discussed in Section 5.4.

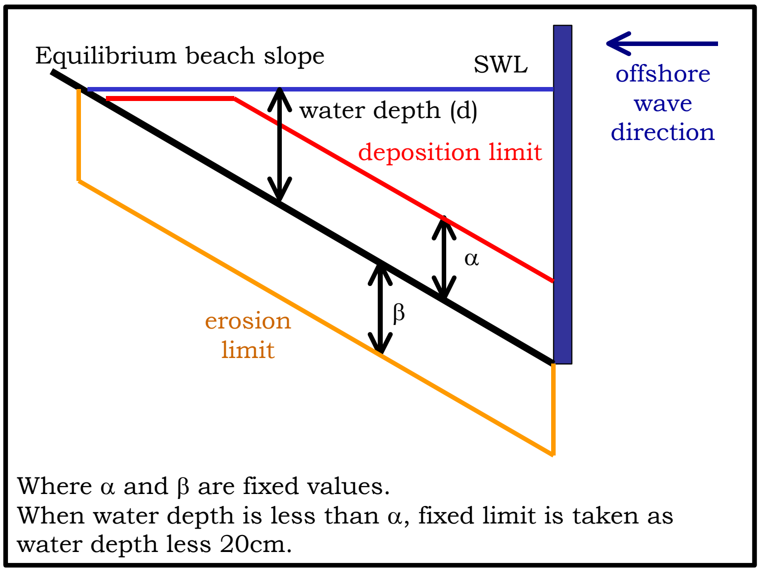

Figure 5.15 Definition of fixed limits.

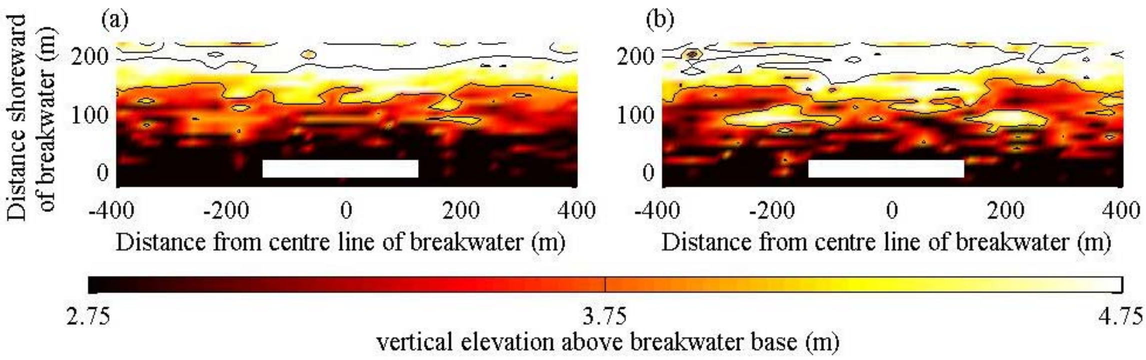

Figure 5.16 Resultant morphology using variable limits of (a) 45% water depth for erosion and 20% water depth for deposition, and (b) 60% and 30% respectively.

The use of smaller variable limits (45% and 20%) stopped deposition from occurring far offshore to some degree where the amount of deposition would have had a noticeable effect on the waves and current above it. Because of this the offshore area is a little patchy, as this has no effect on the overall sediment transport objective function value calculations. This also limited the growth of the salient that was starting to form in the lee of the breakwater.

The further relaxation of the variable limits encouraged more deposition and erosion, so that the difference between two grid points could be as much as 90% the total water depth. The resultant morphology can be seen in Figure 5.12 (b), and its results were discussed previously in Section 5.4. A salient has formed in the lee of the breakwater that is more defined than the smaller variable limit results shown in Figure 5.16 (a). The morphology is a little more fragmented than the result using smaller variable limits, as the allowable change in depth between two points is greater. This greater variability generally acts to bend the contour lines however, rather than introducing isolated pockets of erosion and deposition.

Further evidence of the superiority of the relaxed variable limits can be shown by a comparison of the objective function value pathways. A plot obtained of the objective function value reduction using narrower variable limits is show in Figure 5.17 (a), while Figure 5.17 (b) shows a plot of the objective function value decrease for the relaxed variable limits. The minimum objective function values obtained with relaxed and narrow limits were 6.6×10^{-3} and 1.02×10^{-2} respectively. This shows the relaxed variable limits were able to produce an equilibrium morphology with a reduced minimum objective function value.

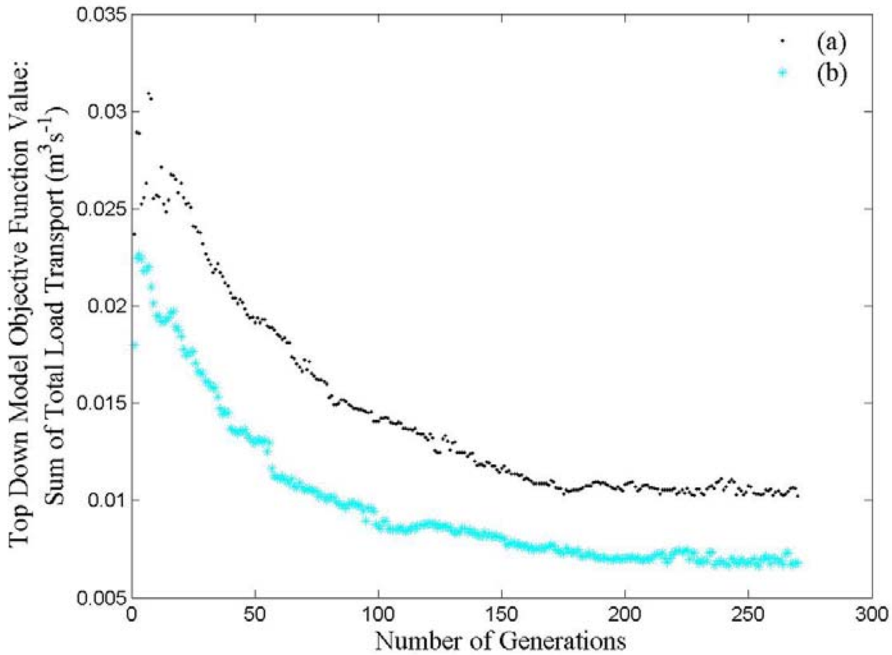

Figure 5.17 Path of objective function using variable limits of (a) 45% water depth for erosion and 20% water depth for deposition, and (b) 60% and 30% respectively.

In both variable limit runs, the objective function decreased for approximately 150 generations before reaching a plateau. The optimisation module was still able to reduce the objective function value after 100 generations, despite the morphological grid size being reduced at this point.

A comparison can be made between the use of fixed limits for the randomly defined morphologies and the use of variable limits linked to original water depth. The use of variable limits produces more continuous morphologies than fixed limits, with less fragmented pockets of deposition and erosion interspersed with the main morphological deposition lope. The optimised morphology using fixed limits of ±2.5m is shown in Figure 5.18.

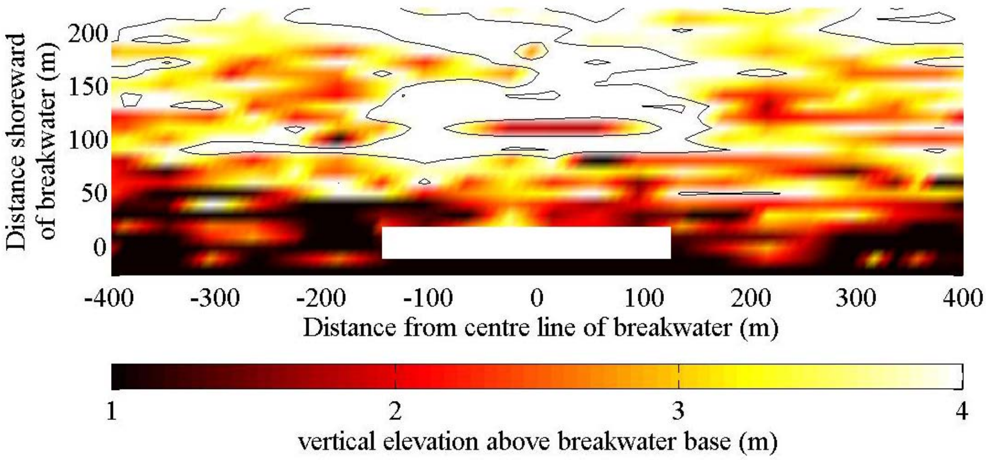

Figure 5.18 Resultant morphology using a top-down model with fixed random elevation limits of ±2.5m.

The fixed limit model was able to pinpoint deposition forming towards the breakwater but a small erosion hole developed, encircled by the deposition, as well as various other small pockets of erosion and deposition interspersed throughout the model. The wave and current models are not designed for large jumps in elevations. This allowed the erosion hole to occur in the deposition mound. It was masked by the deposition and had little effect on the wave and current calculations and hence the objective function value. The morphology was more fragmented and uneven than the variable limit results. The contour lines were interspersed by deposition and erosion, rather than bending around as in the variable limit morphologies.

The fixed limit model was able to reduce the objective function to a minimum value of 0.0035, after 223 generations. The path of the objective function for the fixed limit model can be seen in Figure 5.19. It shows the steady improvement of the objective function value once the grid size was reduced after 100 generations. When the grid size was further reduced after 200 generations, the scatter became greater as the morphology was able to become rougher when the distance allowable between areas of erosion and deposition was reduced. The fixed limit model was able to obtain a smaller objective function value than the variable limit model, as it was able to unrealistically erode greater amounts of sediment near the shoreline, deepening the area and reducing sediment transport.

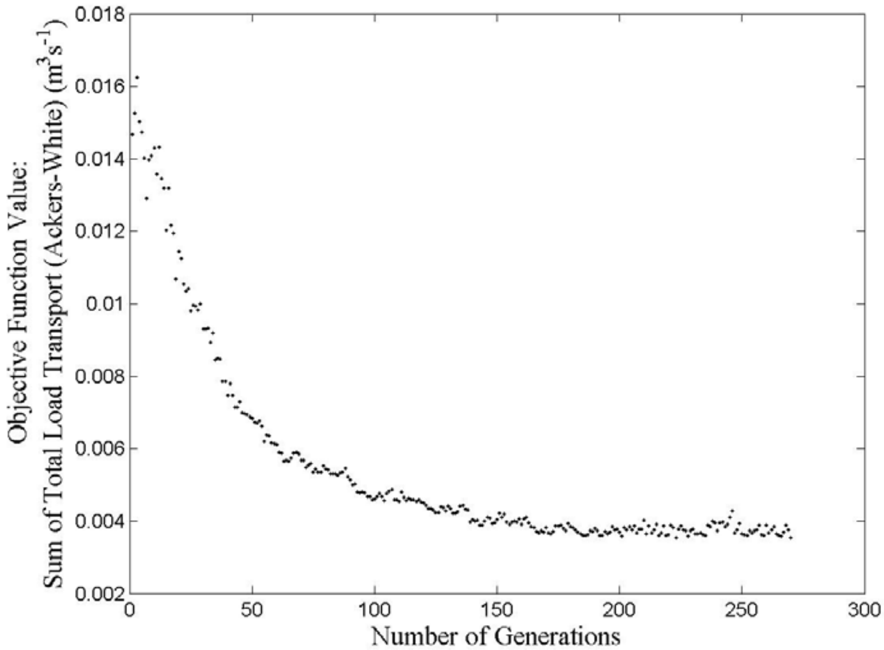

Figure 5.19 Path of the objective function using atop-down model with fixed random elevation limits of ±2.5m.

The top-down method discussed in this Section, produced a smaller objective function value, and more realistic solution, than the use of a coarse or fine fixed grid. The use of fixed grid GA-SA optimisation is discussed in the following Section.

5.4.3 Coarse and Fine Fixed Grid Size Comparisons

This Section discusses the use of a fixed grid size as opposed to a top-down model for either variable or fixed random elevation limits.

Variable Random Elevation Generation Limits

A comparison was made to show the positive effect the use of a top-down model had, as opposed to a fixed morphological grid size, either coarse or fine where both models being compared contained a variable limit. The resultant optimised morphologies obtained using a coarse grid space of 80m and a fine grid space of 20m are shown in Figure 5.20. These can be compared to the top-down result shown in Section 5.4, Figure 5.9. All three runs used the same GA parameters and the same variable random elevation limits.

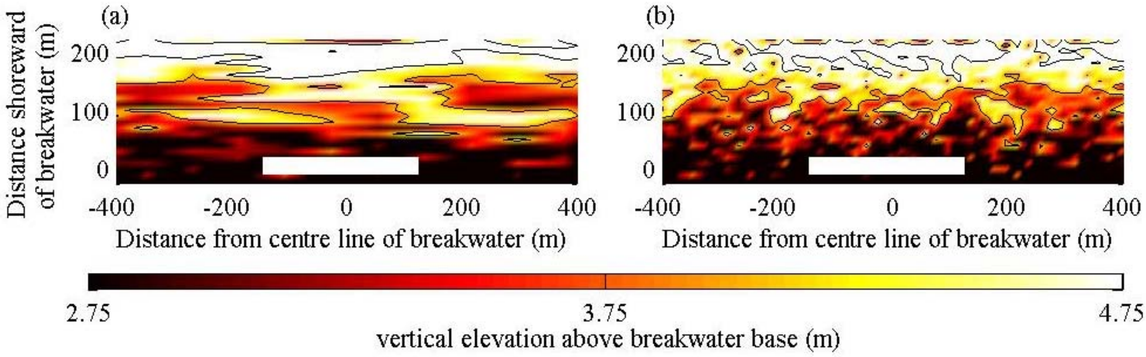

Figure 5.20 Comparison of results using variable random elevation limits and a fixed morphological grid size of (a) 80m and (b) 20m.

A comparison of the morphologies shows that the use of a top-down model produces a smoother, better-defined morphology. The use of a coarse grid was able to pinpoint the area where the salient formed, in the lee of the breakwater, but due to the grid coarseness, it was not able to define the exact shape. Particularly in the deeper water areas offshore, where the elevation did not have as great an effect on sediment transport and hence the objective function, large areas of deposition occurred.

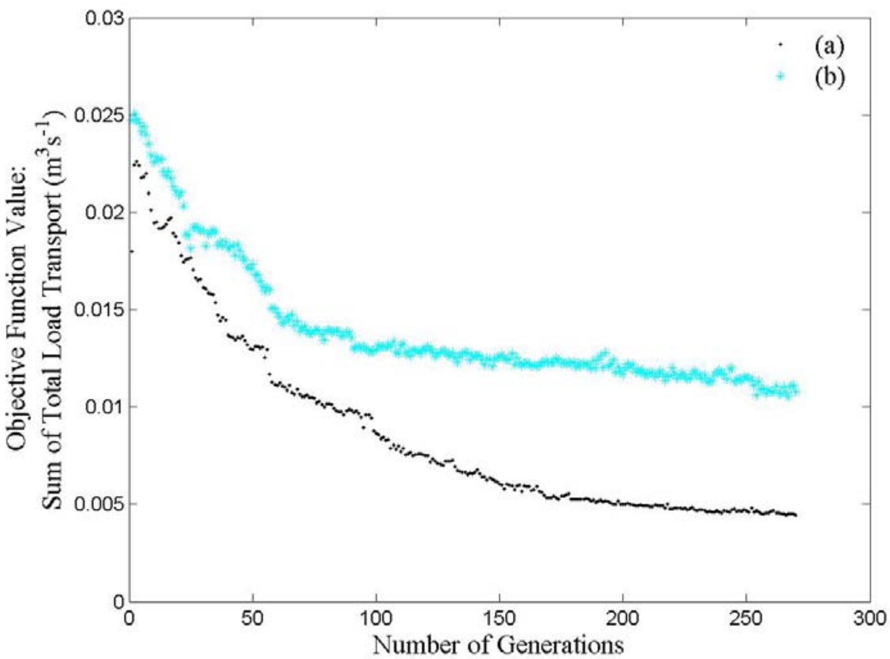

Figure 5.21 Path of objective function using fixed morphological grid size of (a) 80m and (b) 20m.

The use of a fine grid involved a large number of decision variables. This swamped the optimisation module as the solution space was much larger in which it had to search for a combination of morphologies close to the global optimum. This greatly increased the run time, making the search uneconomical. It was not able to decipher an optimal morphology, as can be seen by a comparison of the objective function paths in Figure 5.21, where the minimum objective function values obtained for the coarse and fine grid runs were 0.0044 and 0.0105 respectively. The run with the coarse grid obtained a lower objective function value more efficiently, as it has fewer decision variables so the optimisation module was searching a smaller solution space. It was not able to determine a detailed morphology, however. This was the advantage of the top-down model. It was able to use the faster, more efficient traits of the coarse run, with the detail associated with the fine run.

Similar observations were made by a comparison of a top-down model to fixed coarse and fine morphological grid runs with fixed random elevation generation limits.

Fixed Random Elevation Generation Limits

A comparison was made to show the positive effect the use of a top-down model had, as opposed to a fixed morphological grid size, either coarse or fine where both models being compared contained a fixed random elevation generation limit. This Section outlines the results obtained using either a coarse or fine grid and shows that the results obtained using a top-down model are superior. A morphology found using a fixed coarse morphological grid of 50m by 10m is shown in Figure 5.22 (a). This is in contrast to the use of a fine morphological grid of 30m by 10m, as shown in Figure 5.22 (b). The fixed limits used for the random elevation perturbations were 4m in deposition and 3m in erosion, with respect to the initial equilibrium beach profile. The results shown occurred after the GA had been run for 200 generations with a population of 50 using a coarse grid. The fine grid results occurred after both a GA and SA had been applied.

The results in Figure 5.22 (a) show that using a coarse fixed grid the morphology started to form a salient stretching offshore towards the breakwater, but the morphology is very fragmented compared to that obtained using a top-down model, as discussed in Section 5.4.2 and pictured in Figure 5.18. This was partly caused by the large variation in elevation that two adjacent points may take on, up to 7 metres difference in elevation in the longshore direction and 7.5 metres difference between grid cells in the cross shore direction. The large morphological grid size also induced deposition either side of the breakwater, as this was the only way in which deposition was able to occur behind the breakwater, depending on the positioning of the decision variable defined elevations.

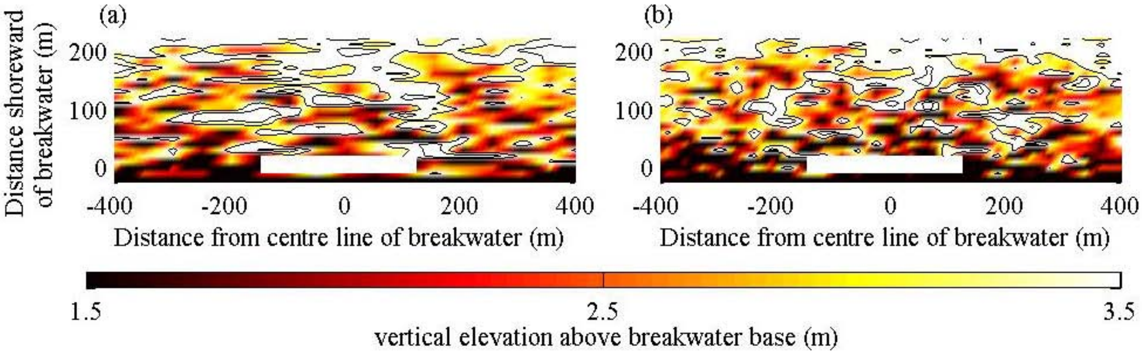

Figure 5.22 Equilibrium morphology predicted using a GA, with a (a) 50m morphological grid size and (b) using a combined GA-SA with a 30m morphological grid size. Fixed limits of 4m deposition and 3m erosion, either side of the initial slope were imposed.

The resultant morphology using a fine fixed morphological grid space, after optimisation using the combined GA and SA, can be seen in Figure 5.22 (b). Here the scattering due to the use of too many decision variables is evident. The optimisation module became overwhelmed due to the larger number of decision variables and was less effective in its searching. The pattern is too fragmented to be able to clearly decipher a salient or tombolo type morphology.

The path of the objective function value for the fine morphological grid can be seen in Figure 5.23 (a). It progressed with a milder slope than the coarser morphological example, due to the greater number of decision variables that it needed to optimise. A minimum objective function value of 0.0058 was obtained after the GA, which is slightly greater than that of the coarser grid, which obtained a minimum value of 0.0044. This was due to the larger number of decision variables involved when a fine morphological grid was used. This causes the optimisation module to become overwhelmed and search less effectively. This has been observed in other optimisation studies that involve large numbers of decision variables (Franconi and Jennison, 1997).

After 200 generations the GA solution appeared to stagnate. A simulated annealing algorithm was utilised to further reduce the objective function value to 0.0051. The path of this further reduction can be seen in Figure 5.23 (b).

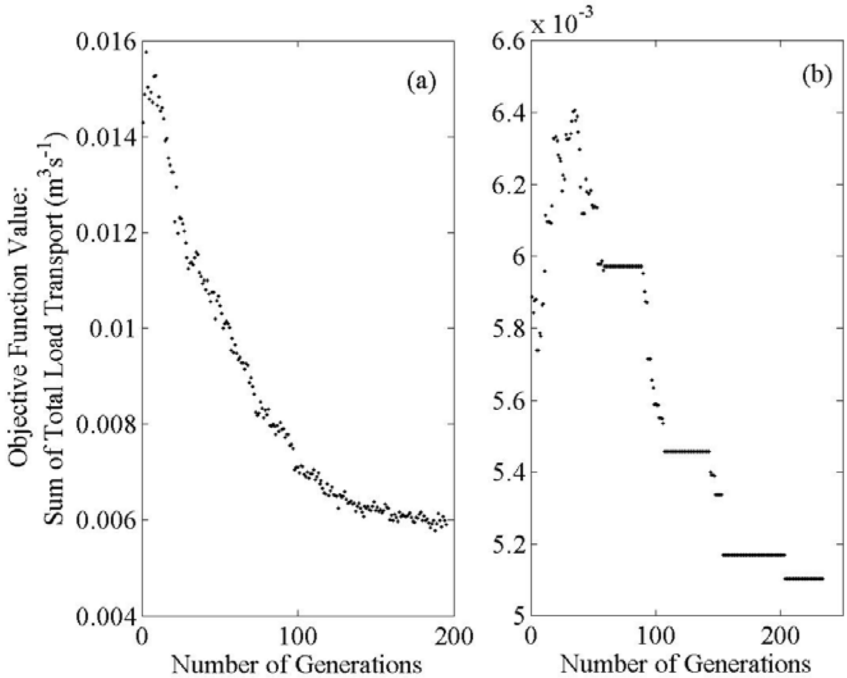

Figure 5.23 (a) Path of the objective function using (a) a GA and (b) a follow on SA, with a 30m morphological grid size and random elevation limits of 4m deposition and 3m erosion.

5.4.4 Use of Different Fixed Limits with a Coarse Morphological Grid

A sensitivity analysis was performed to determine the effect of the fixed limits on the formation of the salient in the lee of the breakwater. A number of different fixed limits were trialled using a coarse morphological grid, to see whether limiting the number of possible elevation solutions by reducing the limits within which random decision variable elevations were chosen, had the desired effect of reducing the solution space and allowing a more realistic morphology to be determined. However, a trade-off occurred, as if the limits became too narrow, the morphologies that gave minimum objective function values were excluded from the solution space.

The resultant morphology using the same coarse morphological grid of 50m, as discussed in Section 5.4.3, but smaller vertical limits, is shown in Figure 5.24. The limits used for the random elevation perturbations were ±1.5m with respect to the initial equilibrium beach profile. The GA used a population of 50 and was run for 230 generations.

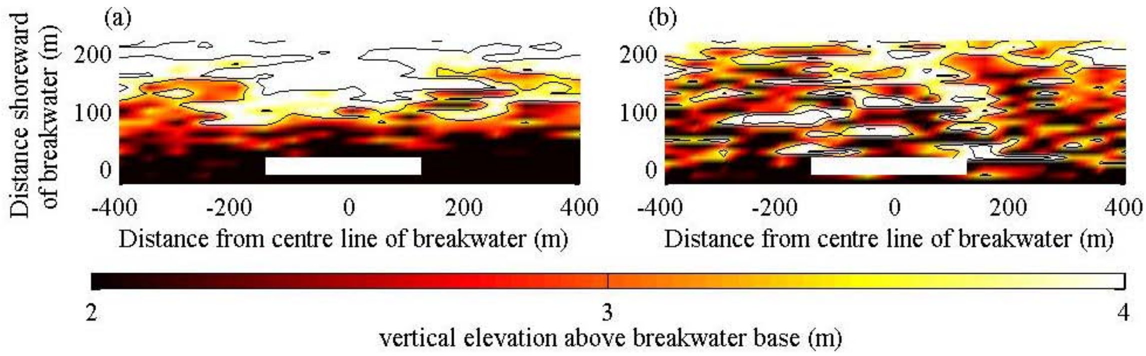

Figure 5.24 Equilibrium morphology predicted using a GA, with a 50m morphological grid size and random elevation limits of (a) ±1.5m and (b) 4m deposition and 3m erosion.

This morphology has formed a much more definite deposition mound in the lee of the breakwater. This suggests that the limits may be overly strict, with the system unable to form the equilibrium morphology that best minimises the objective function value. A comparison of objective function values confirmed this (see Figure 5.25). For the limit of +4m and –3m, the minimum objective function value was 0.0044, whereas the minimum objective function value for the limit of ±1.5m was almost double (0.0080). This was because the system cannot deposit and erode more than the specified limits. The solution was a lot less fragmented, as there was less choice in elevation for each decision variable. As was shown in Section 5.4.2, a variable limit in proportion to water depth, improved the results.

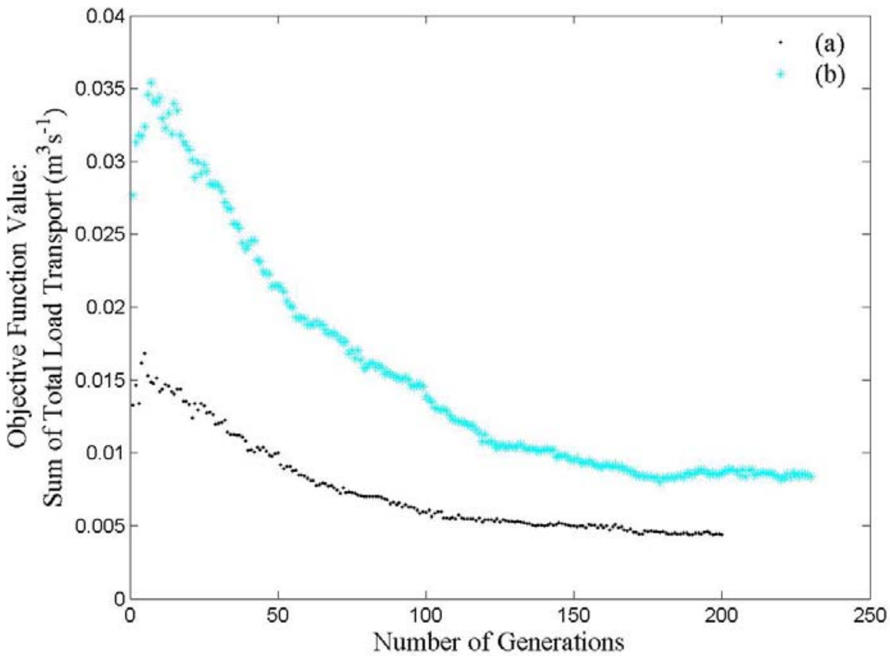

Figure 5.25 Path of objective function using (a) a +4m and –3m change in elevation limit and (b) ±1.5m elevation limit.

A greater flexibility in the amount the equilibrium slope can erode or deposit, can allow for more complex morphologies to develop, but increases the solution space to be searched. In contrast, a small area between which the random elevations of the sea bed may be chosen from, allows for areas of erosion and deposition to be more easily identified, but the value of the objective function may suffer, as these areas may reach the limit of erosion or deposition and be unable to continue the trend.

5.4.5 Inclusion of Minimum Elevation Variance in Objective Function

Based on earlier results, building upon the objective function that used variable limits with total sediment transport minimisation, a further variation to the objective function was trialled. This further variation involved the inclusion of elevation variance in the objective function, where the variance was minimised in conjunction with the sediment transport, by multiplying the two together to form a new objective function, as shown in Eq. (5.10).

$$OF = \left(\sum_{all\ i,j} \left| q_{ij} \right| \right) \times (\mathrm{var}) \qquad (5.10)$$

where *var* is the variance in elevation over the area where random elevations are defined.

The inclusion of minimum variance was anticipated to smooth the solution and reduce fragmentation. This is because to minimise variance, the solution wants to make the difference between grid cells as small as possible. Minimum variance has been included in a number of entropy-based studies of river environments (Langbein and Leopold, 1964; 1966; Scheidegger and Langbein, 1966; Karcz, 1980; Yang 1987; 1994).

This further addition to the objective function was able to reduce the undulations in the predicted morphology, as can be seen by a comparison of the new morphology in Figure 5.26, with that in Figure 5.9.

An analysis of the objective function path, given in Figure 5.27, shows that the objective function made only minor improvements when the grid size was reduced after 100 generations. This was because of the way the objective function was set up. The objective function was trying to minimise variance, so the introduction of a finer grid, with more potential for greater variation between points, created a worse objective function value. It may be that the top-down model is not ideal when variance is included in the objective function calculations, and a finer grid by itself may produce better results.

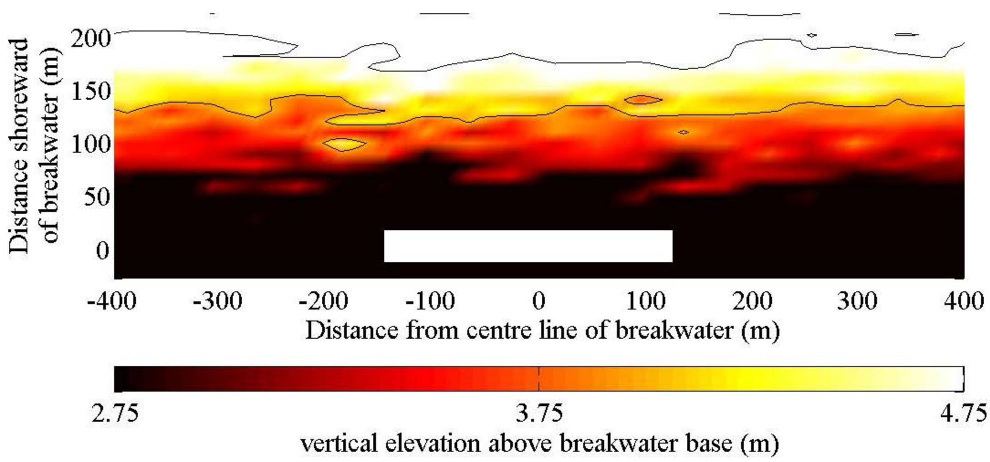

Figure 5.26 Resultant morphology using top-down model with minimum variance inclusion in objective function.

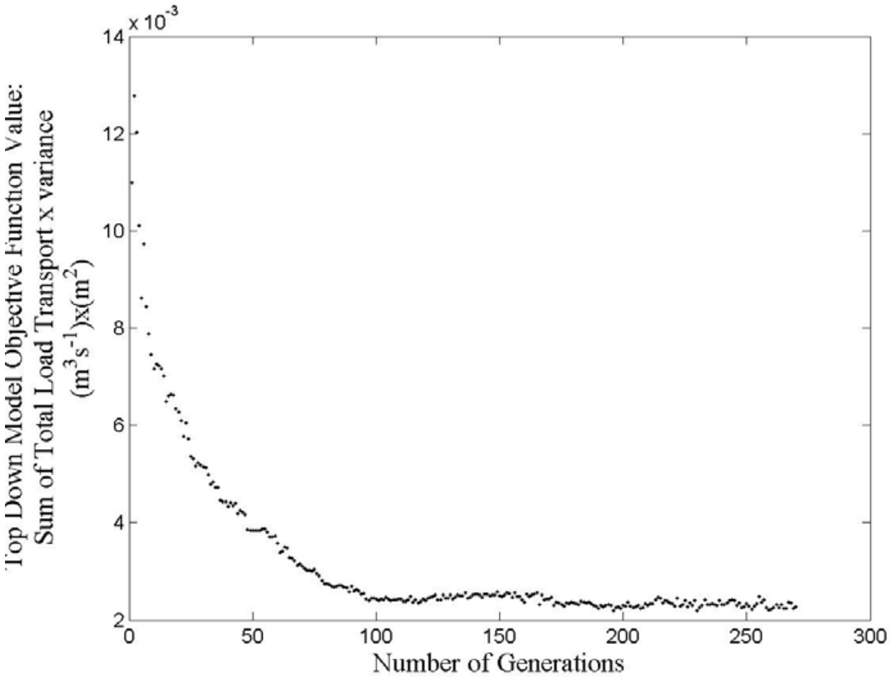

Figure 5.27 Path of objective function using top-down model with minimum variance inclusion in objective function.

A further run was performed using a fixed grid size of 40m, with no top-down component, to see the effect of variance inclusion if grid size was fixed, and therefore the problem of reducing the grid size and introducing greater variance was eliminated. The morphology obtained after 200 generations is shown in Figure 5.28.

As can be seen in this Figure, when a comparison is made with the top-down model where variance was not included, the number of deposition mounds and erosion holes spread around the modelled area has been reduced. The morphology does not predict the salient shape as well, but this may be due to the stagnation of the GA.

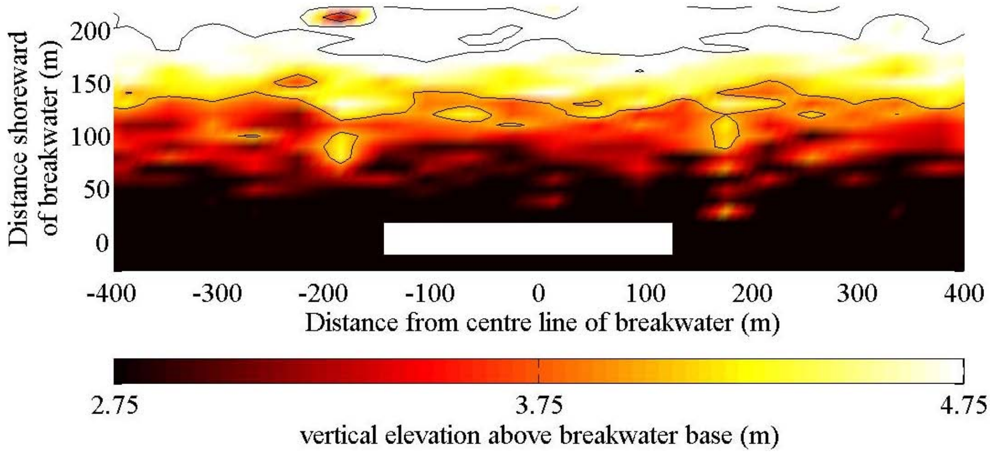

Figure 5.28 Resultant morphology with the inclusion of minimum variance and a fixed morphological grid size of 40m.

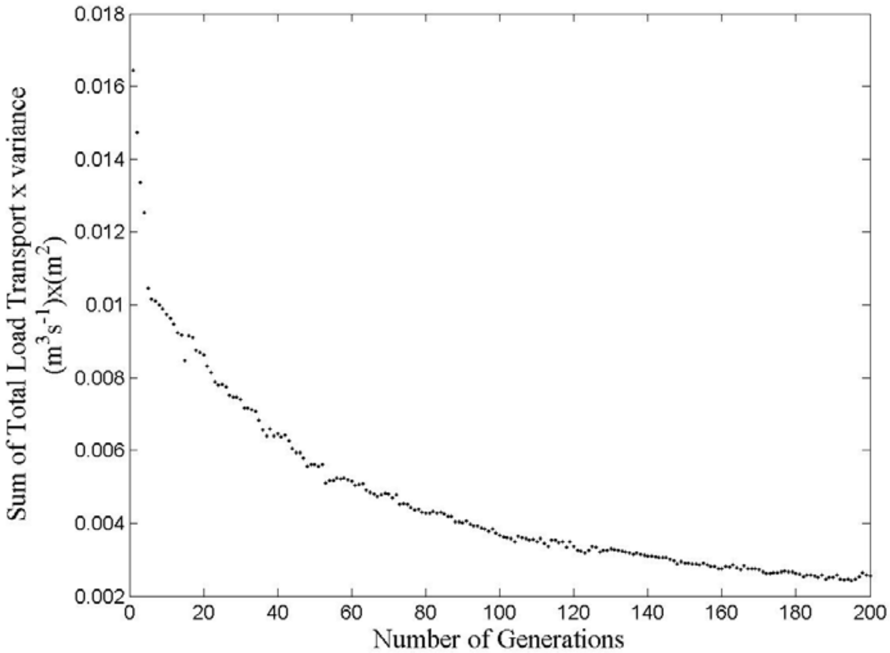

Figure 5.29 Path of objective function using fixed morphological grid size of 40m, with minimum variance inclusion in objective function.

The path of the objective function, which found a minimum value of 0.0024 after 195 generations, is shown in Figure 5.29. In comparison with the top-down model results, the path of the objective function does not stagnate after 100 generations, as at this point there was no reduction of grid size. The refinement of objective function was shallower however, as the number of decision variables was large, so the GA was less efficient, as it needed to search a very large solution space.

To further test the effect variance inclusion had on the smoothing of morphology, results were obtained using a fine morphological grid of 20m. These were then compared to the morphology obtained using a fine morphological grid with no inclusion of minimum variance. The morphologies from both these combinations can be seen in Figure 5.30.

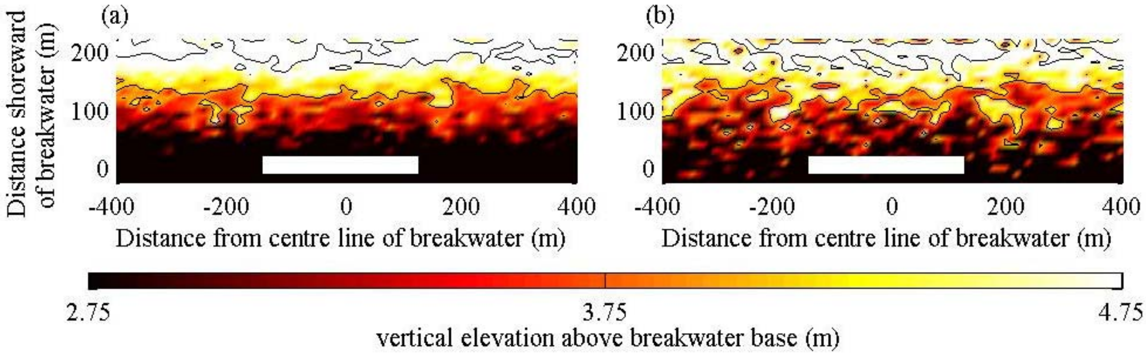

Figure 5.30 Comparison of results using a fine morphological grid (a) with and (b) without minimum variance included in the objective function calculations.

As a comparison shows, the inclusion of variance in the objective function calculations does indeed limit the random undulations, forming a more homogenous morphology. A similar morphology developed in both cases, but without the inclusion of variance, the elevation difference between two adjacent cells was more severe.

The paths of the objective functions with and without variance are shown in Figure 5.31, where minimum values of 0.003 and 0.0105 were obtained respectively. The use of a fine morphological grid meant that the number of decision variables was large, so the GA became less efficient, as it needed to search a very large solution space. This is evident in the shallowness of the objective function value paths, as they obtained a minimum value that was larger than that obtained using the coarser grid of 40m. The optimisation module became lost in the solution space, as it was trying to minimise locally the difference between elevations of two adjacent cells. As this could be quite large, the effect of global sediment transport minimisation by forming a stable salient deposition lobe in the lee of the breakwater does not have as great an influence on the objective function calculations.

A comparison of the objective function value paths with and without the inclusion of variance shows that without the inclusion of variance the objective function value was not as limited with each generation, so the spread of values was greater. This is because there is more scope for a variation in elevation without necessarily having a negative impact on the objective function value, thereby increasing the value. The inclusion of variance in the objective function acted to force the model to form a less fragmented, more homogeneous morphology.

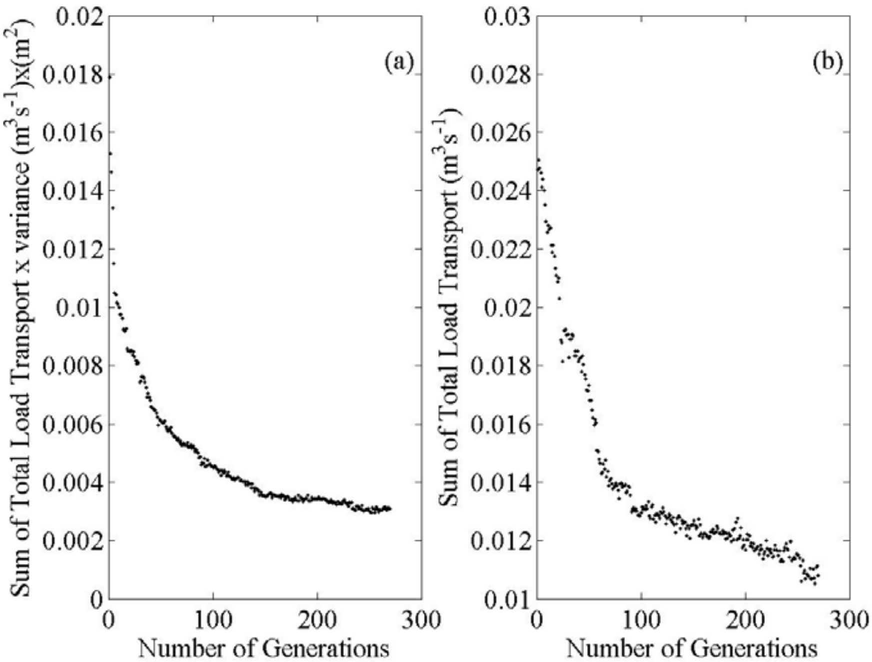

Figure 5.31 Path of objective function using fixed morphological grid size of 20m, (a) with minimum variance and (b) without minimum variance inclusion in the objective function.

5.5 Discussion

The results described in this Chapter do not predict ideal morphology, but they do pinpoint the areas where deposition and erosion are likely to occur, using a different approach to that of traditional time-stepping type models. Optimisation is utilised, rather than the repositioning of sediment over time. This means that the actual formula used for the sediment transport does not have to be as exact quantity wise, rather the limits where transport will no longer occur become important. It is a different slant to traditional models. This new method removes the need to model the individual time movement of sediment, comparing end morphologies directly to one another.

The results of the Nicholson et al. (1997) study found that in general the models predicted partially submerged tombolos when run for an extended period of time, with salients forming initially. Empirical equations were also solved, suggesting that a tombolo was the most plausible solution. In the results tabled in this Chapter, the run using a coarse grid and large limits predicts an equilibrium morphology with deposition between the SWL and the breakwater. Similarly, in the top-down model, submerged deposition extends towards the breakwater. The run using a coarse grid with small limits predicts a salient. This is due mainly to the specified run variables. In this case, the limits only allow a small change in depth, so that in deeper water, the bottom elevation cannot be raised high enough to have a positive build-up and hence does not affect the sediment transport in the system. This can be seen in the objective function for this case, being greater than the coarser limits, where the bottom elevation had a greater possible variation.

The introduction of variable limits, related to water depth, was able to improve the morphology predictions. It was able to reduce the fragmentedness of the predicted morphology, by reducing the difference in elevation between cells in shallow water, but still allowing for greater variation in elevation in deeper water. Further manipulation of the limits may aid in better predicting the equilibrium morphologies.

The optimisation method is limited by the objective function description. In deeper water, sediment is below the threshold for transport and therefore excluded from the objective function calculations. This limits deposition in deeper water. It is similar in a way to the lagoon study in Chapter Four, where the deposition mounds were not accurately predicted by the objective function as the objective function was designed for an erosional environment.

As can be seen in Figure 5.23 (a) and (b), the SA was able to reduce the objective function value obtained with the GA after it had begun to stagnate. This is because, rather than manipulating whole populations as in the GA, where multiple elevations may be changed simultaneously, the SA only changes a single elevation. The SA then compares the objective function obtained using this small change to the previous morphology, accepting or rejecting it based on the Metropolis criterion. Figure 5.23 (b) shows that when the temperature is reduced, fewer changes are accepted and the objective function value and morphology remain the same for a number of temperature drops. Further manipulation of the variables used to control the GA and SA simulations, may be beneficial in reducing the objective function value and obtaining more realistic morphologies.

The effect of a coarse grid can clearly be seen by a comparison between the coarse and fine grid morphologies of Figure 5.22 (a) and (b) respectively. The reduction in decision variables required for optimisation in the coarse grid is able to pinpoint more effectively areas of deposition and erosion. However, the large grid size means that the accuracy of the positioning is compromised, with deposition occurring outside of the lee of the breakwater due the overlapping of grid cells outside the immediate vicinity. Unfortunately, when the morphological grid size was reduced, the solution space became too large and the global optimisation search methods became too inefficient, computational time wise, to cope with the problem. This is a problem of the global optimisation methods ability to deal with large numbers of decision variables, as was observed by Franconi and Jennison (1997). The top-down model was an attempt at refining the grid size problem. It allowed the model to initially pinpoint the correct areas of deposition and erosion, before a finer grid better defined the actual morphology. This worked to some extent but the residual of the coarse grid size was still present. One solution might be to run the finer part of the top-down model for a greater number of generations, or use an SA to refine the solution. However, this would further increase the computational time required and may be infeasible.

Minimum total sediment transport throughout the system as the objective function was used as an exploration tool to determine the feasibility of optimisation based morphological modelling, rather than the traditional time-step based modelling. There are many refinements that could be made to improve the performance of this objective function, such as the inclusion of slope effects. The use of a more detailed hydrodynamic model may also aid in the improvement of morphological equilibrium predictions.

5.6 Conclusions

A modelling method has been developed that is able to predict equilibrium morphological development in the lee of shore parallel, detached breakwaters. It is able to utilise global optimisation routines to compare objective functions based on minimum total net sediment transport, to predict which of the randomly defined morphologies is closer to equilibrium. It is able to start with a completely random, infeasible solution, and quickly modify this to a more probable equilibrium morphology. The use of a top-down model, where the morphological grid size is refined as the optimisation routine progresses, greatly enhances the ability of the method to pinpoint equilibrium morphologies efficiently. Future work would be beneficial to further develop and refine the objective function, to include other factors that influence the defining of stable equilibrium morphologies.

6 Conclusions and Recommendations

This thesis has developed non-conventional modelling methods, based on self-organisation and entropy, able to predict equilibrium morphologies in coastal environments. A number of laboratory studies have been undertaken and there has been some comparison between the new methods and traditional model results. It has been found that both methods are able to predict acceptable equilibrium morphologies, but that the entropy-based method is more advantageous, as it predicts equilibrium morphologies directly. The major conclusions from the results of this thesis are summarised in this Chapter, with recommendations for future research in this field of equilibrium morphology model development.

6.1 Conclusions

6.1.1 Self-Organisation-Based Method

Chapter Three developed a self-organisation-based model, capable of predicting the equilibrium morphologies associated with channel constrictions and obstructions. This self-organisation-based model utilised a cellular automata framework, with local rules applied on a cellular basis. The rules were based on a critical velocity exceedance for sediment transport and a critical angle of repose for avalanching.

The developed model compared favourably to resultant morphologies from experiments. The self-organisation-based cellular automata model outperformed a traditional process-based model that utilised the same hydrodynamic solver, when a quantitative comparison was made using the Brier Skill Score.

The cellular automata model was then applied to a large-scale field example of a unidirectional flow inlet. It was able to predict the formation of a channel between the inflow and outflow areas, which decreased total global energy dissipation through the system. These findings are further elaborated on below.

Application to a Channel Constriction and Obstruction

A number of laboratory experiments were undertaken to determine the equilibrium morphologies that resulted in a 10m long flume subjected to clear-water scour, with a constriction or an obstruction placed in its centre. The results of these are discussed in Sections 3.2 and 3.5.

The constriction experiments experienced a wall-jet like flow, with sediment deposition skewed to one side of the flume when exiting the constricted area. Due to this wall-jet like flow, only the areas of erosion, in the throat of the constriction, were compared to the computer-modelled results. A qualitative comparison between the laboratory morphology, traditional model predictions and the cellular automata modelled equilibrium morphology showed that both models predicted the area of erosion accurately. Although the deposition mound was in the wrong position due to the wall-jet like flow, the cellular automata model predicted a more irregular shape with greater resemblance to the laboratory result. This was a closer qualitative prediction than the traditional model.

Whilst the model predictions were similar, the paths to reach those predictions were quite different. The traditional model used a sediment transport formula, applied at each time step. The cellular automata model used physically-based rules, sediment increments and flow directions, updated at each iteration.

The obstruction experiments did not have the same wall-jet like flow as the constriction experiments and so could be compared quantitatively to the computer model results. The cellular automata model outperformed the traditional model, with a Brier Skill Score of 0.34 giving a good representation of the laboratory results. The traditional model recorded a value of –0.63, giving a poor result due to the misalignment of the depositional mounds.

A number of sensitivity analyses were performed using the obstruction set-up and the cellular automata model. The analyses determined that:

- ★ The model was found to be robust, as similar morphologies resulted regardless of the initial random perturbations of the beds, showing the system's non-reliance on starting conditions.
- ★ The model was also insensitive to the size of the sediment increments moved when rules were violated.
- ★ Grid size was found to impart a large effect on the end morphology obtained, with a finer grid allowing for a more accurate representation of the depositional mound position and shape.
- ★ The use of a variable avalanche angle, rather than fixed allowed a smoother morphology to develop, that had a closer resemblance to laboratory results.

- ★ The uses of different angles of repose and grain size showed the expected results. A large angle of repose allowed steeper slopes to develop, while the use of finer sand allowed a more diffused deposition pattern to evolve.
- ★ The general velocity trends, measured in cross-sectional transects when the system had attained an equilibrium morphology, showed an acceptable agreement when replicated by the hydrodynamic solver.

Application to a Unidirectional Sandy Lagoon

The developed cellular automata model was also applied to a large-scale, unidirectional flow lagoon system example, as discussed in Section 3.9. The model was able to predict a channel forming between the inflow and outflow channels of the system. As the system self-organised, the global energy dissipation between the inflow and outflow channels was reduced. This was in agreement with the theory that states that at equilibrium, a system has a minimum rate of energy dissipation. This theory was then utilised in an entropy-based optimisation model as the basis for an objective function calculation. The conclusions from the development of this entropy-based model are discussed below.

6.1.2 Entropy-Based Method

Chapter Four developed a model based on entropy principles. Optimisation was utilised to minimise an objective function value, which was calculated based on global energy dissipation and local penalties. These local penalties were applied to morphologies with excess erosion or deposition, or an angle between cells that exceeded an angle of repose. Global energy dissipation was calculated by a consideration of the energy lost by the water of the system between the fixed inflow and outflow channels.

The objective function values were minimised using a combined global optimisation module, where first a genetic algorithm (GA) and secondly a simulated annealing (SA) algorithm was applied. This combination was found to produce the best results when applied first to a test situation, which solved for flow around a plate in a channel, and secondly in a number of case studies. The results found that there was good quantitative agreement between the GA-SA optimised flow pattern and that obtained using a standard hydraulic solver, with a value of 0.28 being obtained for the RMAE comparison value.

The developed entropy-based model fills a gap in research. It has been used to examine detailed, two-dimensional morphologies, extending previous river formulations that investigated large-scale, planform environments. The method was applied to coastal, complex environments, and detailed comparisons were made between the new model predictions and those of traditional models and laboratory findings.

The model was applied successfully to several different systems, including:

- ★ A sandy lagoon system with unidirectional flow, similar to the system to which the cellular automata model was applied in Chapter Three.
- ★ A lagoon with flow reversal.
- ★ Finally, the model was applied to a laboratory scale unidirectional lagoon, with the model predicting a favourable morphology when compared to laboratory results.

The following sections outline the conclusions made from the use of the optimisation model to these examples.

Application to a Unidirectional Lagoon

A unidirectional lagoon was modelled using a similar set-up to that examined in Chapter Three. A comparable morphology was obtained using the optimisation method, rather than a traditional process-based time-step method or the cellular automata method discussed earlier. The initial optimisation of the model using a GA formed a basic channel, which was deepened by the subsequent application of SA algorithms (see Section 4.3). Both the global energy dissipation and local penalties were required to form an equilibrium morphology. If only the global energy dissipation was minimised, erosion occurred throughout the whole sandy lagoon. Conversely, if only the local penalties were optimised, a channel formed but did not deepen.

The results showed that the entropy-based method is more advantageous than the self-organisation-based method, as it predicts equilibrium morphologies directly. The self-organisation-based method rearranges the sediment gradually, using rules and sediment increments in a cellular automata model, while the entropy-based method finds the equilibrium morphology using optimisation-based refinements, independent of sediment transport. Instead it utilises an initiation of sediment transport relationship to exert penalties on nonequilibrium morphologies, in conjunction with a minimisation of energy dissipation throughout the system.

Application to a Lagoon with Flow Reversal

The method used to model a lagoon with flow reversal was similar to that employed in the unidirectional flow situation. The effect of flow reversal was included by combining the objective functions obtained when flow entered and exited the lagoon through inflow and outflow channels in both directions. This is discussed in detail in Section 4.4.

The inclusion of flow reversal in the lagoon model led to the development of a wider channel between the fixed bed entrances and exits. Larger depositional mounds also formed, which helped to direct the flow into the centre channel. Good qualitative agreement was found between the entropy-based model result and that of the morphology associated with the River Murray estuary.

Application to a Laboratory Sized Lagoon

A laboratory study was undertaken in a unidirectional flow flume, with water entering an erodible bed area through a narrow fixed bed channel, and exiting though a similar oppositely positioned channel. Traditional and entropy-based models were then applied to this laboratory situation, with the entropy-based model making superior predictions of the measured equilibrium morphology. The results of this trial were discussed in Section 4.5.

The improved performance of the entropy-based model is because the conventional model was very dependent on initial conditions, and predicted the formation of a channel on the opposite side of the flume to where it occurred in the laboratory experiment. The entropy-based model was able to predict the correct position of the erosional channel, but had trouble predicting the deposition mound due to the objective function bias to erosional environments. This is an area where further research is required.

6.1.3 Application of Optimisation Method to a Coastal Breakwater

As an alternative to traditional process-based models employed to predict equilibrium morphologies associated with detached, shore-parallel breakwaters, which aid in the design and management of these breakwaters, an optimisation-based model was developed. It is detailed in Chapter Five.

The optimisation-based model makes use of the GA-SA global optimisation method utilised also in Chapter Four. In addition, it uses a top-down model to increase the effectiveness of the GA search. This method starts by optimising a coarse grid, and as it moves towards an optimum value, the grid size is decreased. This allows the model to first pinpoint areas of deposition and erosion, and then refine these areas. The objective function, utilised in conjunction with the optimisation, is based on a minimisation of total sediment transport in the system. The calculations take into account sediment transported due to both the waves and currents of the system.

Random morphologies were initially chosen, where the limits of the randomly chosen elevations were in proportion to the water height at each point above an equilibrium beach slope. This beach slope was taken as being the equilibrium slope present before the placement of the breakwater. The edges of the modelled area not affected by the breakwater were maintained at the equilibrium beach slope. This helped to give reference to the randomly modified elevations and also direct the solution to a more plausible morphology.

A number of different random seeds were then used to show that the modelling method was robust, with similar equilibrium morphologies were predicted with different seeds. The limits between which the random morphologies were initially predicted imparted a large effect on the equilibrium morphologies obtained. If the limits were too narrow, the desired morphology was excluded from the solution space. In contrast, if the limits were too large, the solution space become too big for the optimisation modules to search effectively.

The size of the grids used also imparted a large effect on the predicted equilibrium morphology. The use of a large grid space allowed for the pinpointing of general areas of erosion and deposition, but due to the size of the grid some of these areas overlapped. The use of a small grid size had a similar effect to large limits, in that it greatly increased the size of the solution space. This meant that the computational power required to find an optimal solution became infeasible. The use of a top-down model helped to lessen the effect of grid size on the end solution as it combined a number of different grid sizes.

The developed method differs from conventional methods as it removes the need to model the individual time movement of sediment, rather comparing end morphologies directly to one another. This reduces computational time and helps to alleviate the potential for error amplification due to the time-stepping process. However, the method has some limitations that reduce its ability to predict equilibrium morphologies as accurately as traditional models.

- ★ The large number of decision variables involved lessens the global search routines' ability to local minimum equilibrium solutions.
- ★ The potential for large elevation differences between grid cells due to the randomness of the method lessens the accuracy of the wave and current model predictions.
- ★ The method application is not conducive to smoothing routines, which lessen the elevation difference between grid cells, as these overpower the objective function and force the solution of an unrealistic morphology.

The use of optimisation-based methods in situations with complex environments where waves and currents influence a system with not specific boundaries, such as the breakwater example, does not produce as convincing results as were obtained in the simplified lagoon study. However, the method is able to pinpoint some areas were erosion and deposition occur and warrants further research into possible applications and modifications.

Areas where the elaboration of research undertaken as part of this thesis would be beneficial are detailed in the remainder of this Chapter.

6.2 Recommendations for Further Research

This thesis introduces alternative modelling methods to traditional process-based, time-stepping methods, and relates them to a number of different laboratory and field case studies. This Section outlines areas where further investigations would be beneficial.

6.2.1 Self-Organisation-Based Model

Constriction and Obstruction Experiment

To overcome the wall-jet like flow experienced in the constriction experiments, it is recommended that further tests be carried out using a wider flume, with the results compared to the cellular automata model results. The use of a three-dimensional hydrodynamic solver would take into account the three-dimensional effects of the wall-jet like flow. The use of a three-dimensional model would also improve the results of the obstruction experiment cellular automata model, and further investigation into this would be beneficial. However, the use of more complex models would increase the computational time requirements and reduce some of the benefits of using a cellular automata model. The use of a more detailed model would improve results regardless of whether a conventional or self-organisation-based model was utilised.

6.2.2 Entropy-Based Model

Deposition Modelling

Deposition is predicted to some extent by the entropy-based model, particularly in the reversing flow lagoon. However, the objective function has been designed with a bias towards predicting erosive environments, due to the river morphological research where the inspiration for this method came from. It would be beneficial to modify the objective function to account for deposition more actively. A number of different objective functions were trialled based on the Exner equation, but due to the non-time-dependent nature of the method, they were unsuccessful. This is also an area where further exploratory research is required.

The next step to improve the flow reversal lagoon modelling is the investigation of a sediment budget function, which could limit the system to the correct sediment loss/gain observed in the field.

The improvement of the entropy-based model to predict the equilibrium morphology of the laboratory lagoon experiment may be attained through the use of a three-dimensional hydrodynamic model to better predict the flow patterns involved in the sediment transport. Again, the entropy-based method was able to predict the erosion channel well, but had trouble predicting the correct position for the deposition mound. Further research is required to include components in the objective function calculations pertaining to the correction size and position of deposition.

6.2.3 Breakwater Application

Modelling Parameters

Further manipulation of elevation limits and grid sizes may be beneficial in making better predictions using the optimisation-based method to determine equilibrium morphologies of detached breakwaters. Further manipulation of the variables used to control the GA and SA simulations such as generation and population size, crossover type and the point at which the SA takes over from the GA is also likely to be beneficial.

Objective Function Modifications

The objective function utilised in the prediction of coastal morphologies associated with detached breakwaters could also benefit from further exploration and inclusions of other factors that influence the attainment of a stable equilibrium morphology. More complex hydrodynamic models could be used in the calculations of the objective function, however this would increase the computation time involved.

Parallel Computing

One future improvement of the method is the use of parallel computing. GA optimisation methods are suited to parallel computing. This is because within each generation there are a number of population members that require the independent calculation of objective function values reliant on values obtained from a hydrodynamic model. If the calculations for each of the population members could be run simultaneously on a parallel computer, the computation time involved would be dramatically decreased. This is a benefit that is not applicable to conventional models, where the current morphological calculations are highly dependent on the previous morphology and simulations are required to be run for extended simulated time periods. The simulation model accounts for the majority of the time taken for each run. The methods discussed in this Thesis reduce the time required to predict equilibrium morphologies, as the simulations are not run for an extended period of simulated time.

6.3 Closing Remark

The modelling methods developed in this thesis are a first step into the use of non-traditional, entropy- and self-organisation-based models for the prediction of complex coastal equilibrium morphologies. They have made use of non-conventional models in order to explore the use of different objective function formulations or self-organisation rules and the sensitivity of these, and have compared the models to laboratory results. There is much scope to expand the initial exploration in this thesis, however, the work documented in this dissertation shows that it is possible to use self-organisation- and entropy-based modelling methods to predict stable, equilibrium morphologies in coastal and river environments.