A Genetic Algorithm Model of Coastal Evolution

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Abstract: Many coastal features such as tombolas, tidal inlets, deltas and sandy beaches adjacent to groynes tend towards an equilibrium shape or morphology. Coastal researchers have used computer models that solve the basic wave, current and sediment processes and applied the resulting information to predict the changes in morphology in a time-stepping process. In the 1960s it was suggested that the concept of entropy could be applied to landscape formation problems to predict the final form, without the need to step forward in time. Subsequently an analytical solution was proposed for channel geometry in a tidal inlet situation. In the current work a genetic algorithm has been used as an optimisation procedure in an attempt to apply the entropy method to predict the form of two-dimensional river and coastal features. An important aspect of the work has been the use of a process-based model to assist in the evaluation of suitable fitness functions that are used in the optimisation. The paper gives details of a laboratory experiment designed to provide data used for model verification, details of the optimisation procedure and results of the comparison between the laboratory data, a traditional process-based time-stepping model, and the genetic algorithm model. Although run times for the genetic algorithm approach are longer than the process-based model it is proposed that the new model will lead to more reliable solutions in some cases and solutions in other cases where the process-based model would be difficult to apply.

Keywords: Genetic algorithm; Coastal modelling; Sediment transport

1. INTRODUCTION

For decades coastal modellers have studied the evolution of beaches, tidal inlets, offshore bars, sand shoals and other coastal features and worked to reproduce their behaviour. The development of methods to predict coastal morphology can be considered as the development of three distinct types of model. According to van Rijn [1998] the main division is between behaviour-related models and process-based models. It is possible to further subdivide the process-based models by singling out the aggregate models (van Rijn refers to them as volume models) where individual coastal features such as a sand shoal or a tidal delta can be considered to act as a single unit.

Behaviour-related models work on an overall coastal feature using parameterised functions and empirical relationships. The numerical solution is that of a convection-diffusion type model. The one-dimensional line model of nearshore depth profiles [e.g. Hanson and Kraus, 1989; Kamphuis, 2000] that can be used to predict changes in the cross shore profile in the presence of river mouths, offshore breakwaters or groynes is a good example of a model of this type. The advantage of the approach is that it is fast and computationally efficient, but a major drawback is that it is largely empirical and does not assist with understanding the fundamental processes at work. More importantly it is necessary to be able to provide empirical information about a feature that is to be studied. This will not always be possible and limits application of the model.

Process-based models use the wave, hydraulic and sediment governing equations (simplified to varying degrees) to describe the development of waves, tides, currents and sediment transport in time. The models are applied over a fine grid of points and solved using either finite difference or finite element techniques. To apply the models it is necessary to have detailed bathymetric data and the time-stepping can lead to long run times.

Aggregate models lump spatially large features such as tidal shoals together so that they can be treated as a single unit in a process-based type model. The advantage is that the underlying processes are still modelled, but over aggregated features. Kraus [2000] gives a good example of this type of model in a paper outlining the long-term behaviour of an ebb tidal delta. The models are not applicable to the situation where it is not possible to assume that the features can be aggregated, and the approach is therefore limited.

Although process-based models have advantages, a major source of potential error in process-based models is the need to model changes in bed bathymetry using a time-stepping procedure. This has a number of problems. It means that if any errors are introduced they can spread throughout the area and spoil the whole solution. In addition, the time step chosen for numerical stability is often very small, even if it is stretched in comparison with the time step used in the hydrodynamic model, leading to long computer run times.

The aim of the study was to develop a new approach for modelling coastal morphology that attempted to determine an equilibrium position, without time-stepping. The key to the method was development of an equilibrium criterion in terms of a fitness function and the application of a genetic algorithm as the optimisation procedure.

In the work undertaken to date the model has been developed for a uni-directional channel situation and the paper outlines results where the model has been compared to results obtained from a laboratory study and a traditional process-based model. The principles outlined in the paper are quite general, and in a later section the application of the model to a coastal situation will be foreshadowed.

2. EQUILIBRIUM AND ENTROPY

The concept of an equilibrium position is often used in the design of coastal remediation programs where the implementation of groynes or offshore breakwaters is based on creating an orientation of the coast such that sand loss and the subsequent changes are minimised. The idea of an equilibrium position was recognised by Wright et al. [1973] who proposed that all natural systems develop towards a state of maximum stability. In the case of erodable channels this was attained when there was: (1) hydrodynamic continuity; (2) uniform distribution of work; and (3) minimum work on the channel boundaries.

The second and third conditions were based on earlier work by Leopold and Langbein [1962] and Langbein [1963] who introduced and developed the idea of using the concept of entropy in morphological systems to determine equilibrium conditions. Leopold and Langbein [1962] did not explain a general method whereby the concept could be applied, but did identify how the final state might be recognized for eroding channels. It should be noted that in the present context entropy refers to the progression of physical situations to their most probable state. Despite the simplicity of the original proposal by Leopold and Langbein the idea has not been widely applied in coastal or river situations.

3. LABORATORY EXPERIMENT

A laboratory experiment was designed to provide verification data for the new modelling approach. A simple unidirectional channel was set up where a constriction in the channel caused a concentration of the flow and a resulting transport of sediment from the throat of the constriction. The flume was approximately 10 metres in length and 0.9 metres wide. The constriction reduced the throat width to 0.25 metres. Water depth was maintained at approximately 0.2 metres by a weir at the downstream end of the flume.

The flow was selected so that the velocity in the main part of the channel was insufficient to transport sediment. The higher velocity through the constriction led to erosion in the throat and a corresponding area of accretion downstream. After a number of hours sediment transport was observed to have ceased. At this stage the bottom bathymetry was measured over a regular grid of points using an automatic bottom profiler. The results were plotted as a contour plot, an example of which is shown in Figure 1.

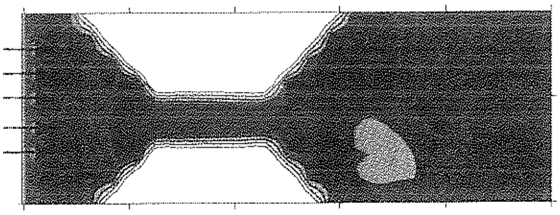

Figure 1. Contour plot of a typical channel bed. The dark areas indicate erosion and the light areas accretion. The contours are plotted at 50mm intervals. The majority of the bed away from the constriction is at the original bed level.

4. PROCESS-BASED MODEL

A process-based model that solved the depth-averaged Navier-Stokes equations and a sediment transport model based on suspended and bed load components proposed by van Rijn [1993] was run until the solution approached equilibrium. Results are shown in Figure 2. The model, 'HYDRA3' (written by the author), solves the momentum and continuity equations. The equations can be written:

Momentum Balance in x direction:

$$\frac{\partial UD}{\partial t}+\frac{\partial U^2D}{\partial x}+\frac{\partial UVD}{\partial y}+gD\frac{\partial \xi}{\partial x}= \frac{1}{\rho}\left(\frac{\partial T_{xx}D}{\partial x}+\frac{\partial T_{xy}D}{\partial y}\right)-\frac{1}{\rho}\tau_{bx} \qquad (1)$$

Momentum Balance in y direction:

$$\frac{\partial VD}{\partial t}+\frac{\partial UVD}{\partial x}+\frac{\partial V^2D}{\partial y}+gD\frac{\partial \xi}{\partial y}= \frac{1}{\rho}\left(\frac{\partial T_{xy}D}{\partial x}+\frac{\partial T_{yy}D}{\partial y}\right)-\frac{1}{\rho}\tau_{by} \qquad (2)$$

Continuity:

$$\frac{\partial \xi}{\partial t}+\frac{\partial UD}{\partial x}+\frac{\partial VD}{\partial y}=0 \qquad (3)$$

where ξ is the surface elevation measured from the still water level; D the water depth; U and V the components of the velocity in the x and y directions respectively; T_{xx}, T_{xy} and T_{yy} are components of the effective stresses due to turbulence; ρ water density; and τ_{bx} and τ_{by} are the bottom friction terms. The bottom friction terms can be written:

$$\tau_{bx}=\rho c_f U\sqrt{U^2+V^2} \qquad (4)$$

$$\tau_{by}=\rho c_f V\sqrt{U^2+V^2} \qquad (5)$$

where c_f is the bottom friction factor and the other terms are as defined previously. The effective stresses due to turbulence can be written:

$$T_{xx}=2\rho\nu_t\frac{\partial U}{\partial x} \qquad (6)$$

$$T_{yy}=2\rho\nu_t\frac{\partial V}{\partial y} \qquad (7)$$

$$T_{xy}=\rho\nu_t\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right) \qquad (8)$$

where ν_t is the eddy viscosity. The model can run using a constant eddy viscosity or it can solve a depth-averaged two equation k-ε turbulence model. In most of the runs presented in the paper a constant eddy viscosity of 0.01 m^2/s was used although the predictions were not sensitive to the value selected. The equations were solved using an efficient Alternating Direction Implicit (ADI) scheme.

Bathymetric evolution was calculated assuming local equilibrium with the sediment transport. This restricts the use of the model to situations where the sediment is predominantly sand. In this case the change in bed level can be written:

$$\frac{\partial z}{\partial t}+\frac{1}{1-\lambda}\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}\right)=0 \qquad (9)$$

where z is the vertical bed dimension, λ is the bed porosity, typically 0.3 - 0.4, q_x, q_y are the x and y transports respectively.

When the test case was run the erosion in the throat of the constriction was predicted and an area of accretion was also predicted downstream. There is general agreement with the results shown in Figure 1, although there are some differences in the detail of the deposition area.

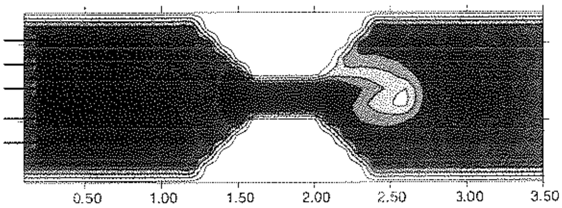

Figure 2. Contour plot of traditional process-based model once the simulation had reached an equilibrium position. Dark areas indicate erosion, light areas accretion. Contours are at 50mm increments and the horizontal scale is in metres.

5. ENTROPY-BASED MODEL

The key to the entropy-based model is the application of a genetic algorithm to solve what is configured as an optimisation problem. A good introduction to the use of genetic algorithms can be found in Goldberg (1989).

The aim of the method is to determine a set of depths over the two-dimensional grid that satisfies an objective function. The objective function describes how well a particular solution satisfies the entropy condition and will be discussed later in the section. To configure the method the depths are represented as a chromosome comprised of a specified number of genes. In this case the individual genes that make up the chromosome are binary integers. In the present scheme the depths at each grid point were represented in terms of four genes that made up a 4 bit string. The solution area was 35 x 12 points giving 420 depths. This led to a total chromosome length of 1680 bits.

The 4 bit representation of each depth gave 16 possible values. The values were selected to represent 25mm steps giving a range of depths at each point of 375mm. A 4 bit string of 0111 represented the undisturbed bed position, 1111 would be a depth that was 200mm less than the undisturbed position and 0000 a depth 175mm below the undisturbed position. A section of the total chromosome and the depth grid are shown in Figure 3.

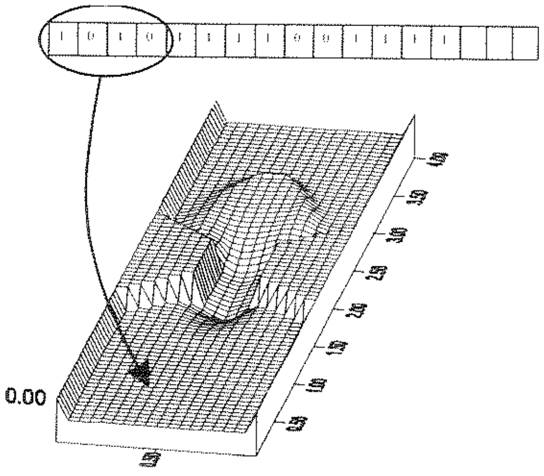

Figure 3. A section of the 1680 bit chromosome that represents the depths over the entire grid. Each 4 bit string represents the depth at one of the grid points.

In the solution an initial random population of chromosomes was generated. The Navier-Stokes flow equations were solved using the depths represented by the chromosome and the objective function evaluated which gave a fitness for each member of the population. The genetic algorithm then ranked the population by fitness and carried out a 'mating' amongst the higher ranked members of the population where offspring chromosomes were generated by a random cross-over procedure. Since only the better solutions had been used in the mating the second generation should be better (have a higher fitness) than the parent generation.

During the mating the genetic algorithm method also allowed for random mutations to add genetic diversity to the solution. The new generation was then assessed for fitness and the procedure continued until the improvement in the generations was reduced to a chosen level or the number of generations exceeded a pre-determined maximum.

A flow chart of the solution procedure is shown in Figure 4. The genetic algorithm code used in the present study was developed by Anderson and Simpson [1996] and written in FORTRAN. This was combined with the HYDRA3 code to form a new program HYDRA3GA which carried out the whole solution. Although Navier-Stokes solvers usually require some time to 'warm up' this was overcome by preparing a stock solution from an undisturbed bed run and using this as the initial solution for each simulation. This reduced the run time required for each evaluation to approximately 1 second on a 667MHz Pentium III PC.

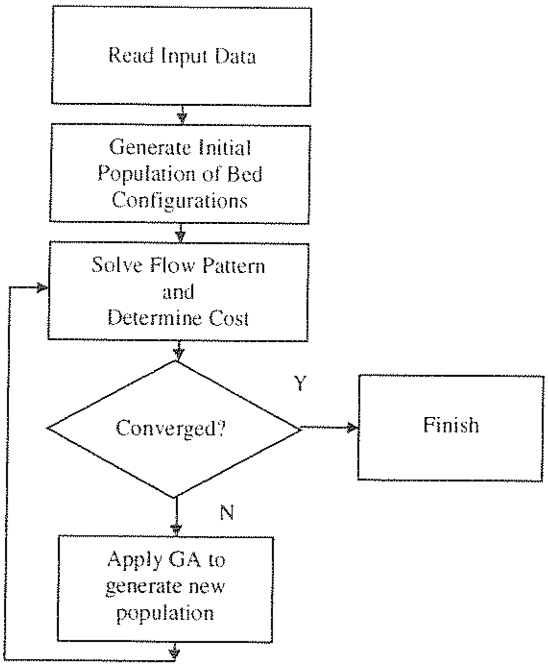

Figure 4. Flow chart for entropy-based model

The key to the application of the method was the development of the objective function or fitness that quantified the extent to which the bathymetry represented by each chromosome in the population satisfied the entropy conditions. As a first approach a simple cost function (inverse of fitness) was determined. It can be written:

$$C = \sum_{i=1,n;\, j=1,m} u_{i,j}^3 + (d_{i,j} - d_0)^2 \qquad (10)$$

where $u_{i,j}$ is the velocity at coordinates (i,j) in the solution domain, $d_{i,j}$ is the depth and d_0 the initial depth over the bed.

The velocity cubed function was selected on the basis that this has been shown to give a good measure of the sediment transport potential [Butt and Russell, 2000]. The measure of bed level variance was used as a simple measure of work done in re-shaping the bed from an initial undisturbed position, and for preventing a solution where all sediment was assumed lost from the channel, leading to maximum depth everywhere. Therefore the optimisation technique searched for solutions that had the lowest potential for sediment transport and the least volumes of erosion and accretion.

The results of the entropy-based model, shown in Figure 5, indicate that even with a simple fitness function the erosion in the channel constriction has been identified. The subsequent accretion is not reproduced, nor would it be expected to since this element of the behaviour was not represented in the fitness function. Work is continuing on this aspect of the problem.

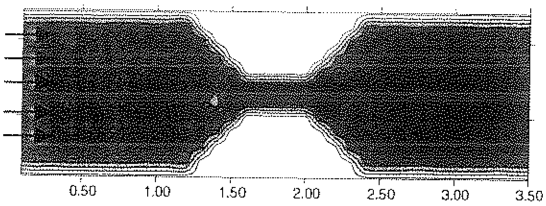

Figure 5. Contour plot of entropy model prediction. The erosion is shown as dark shading.

6. GENETIC FITNESS FUNCTION

One of the issues with the use of genetic algorithms (and optimisation techniques in general) is the problem of knowing whether a solution represents a true solution to the global problem or whether a local maximum has been found. This has been addressed in the study.

During the development of the fitness function a number of potential terms were tested on runs with the process-based model. During this exercise the process-based model was run from start to equilibrium and the selected quantity was calculated and written to file. Tracking the change in the sum of velocity cubed and comparing it to the volume of sediment being transported at each time step demonstrated that velocity cubed was a good measure of solution convergence. This is shown in Figure 6. The reduction in total sediment transport near the final position is also evident. It should be noted in the Figure that the scales on the vertical axes have been adjusted to aid comparison between the two quantities.

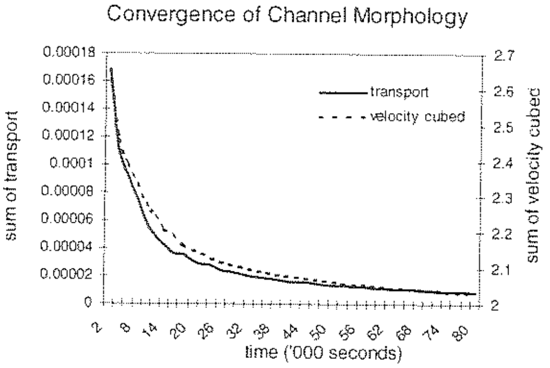

Figure 6. Convergence of solution indicated by the sum of the sediment transport and velocity cubed.

Specific energy loss through the constriction was also tested as one of the optimisation criteria. Its behaviour during a process-based simulation is illustrated in Figure 7.

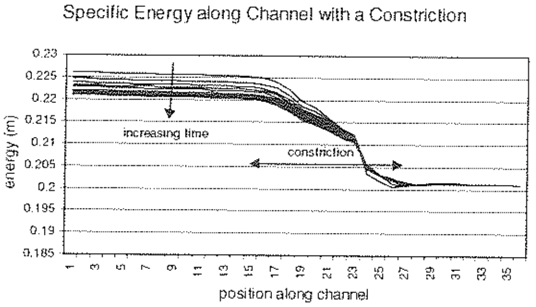

Figure 7. Convergence of solution indicated by the specific energy lost through the constriction.

It can be seen that as the run progressed and material was eroded from the throat of the constriction the energy loss was reduced. Therefore a fitness criterion that was based on minimising the loss should provide a suitable fitness function. The advantage with using specific energy is that it could be applied along streamlines rather than across the total channel width as has been done to date. This will be important in future work where large coastal areas will be modelled. There are also a number of sediment models that use energy as the basis for determining transport.

7. SUMMARY AND CONCLUSIONS

A new type of model has been developed for simulating the morphology of rivers and coastal areas. The model is based on research carried out in the 1960s and 1970s that used the concept of entropy to describe the most probable state for the river or coastal system. The method has been developed using a genetic algorithm to optimise a fitness function based on mimimising the potential for sediment transport. The algorithm mimics Darwinian evolution by deriving solutions on a population by population basis with transformations that tend to improve the fitness of solutions in time.

In the current study the development of river morphology has been demonstrated in the case where a constriction in a channel led to erosion and subsequent accretion at a downstream location. The new model was able to predict the erosion reasonably well, although failed to describe the subsequent accretion. This is due to the form of the fitness function which is currently under development.

At present run times for the entropy-based model are long since a large number of generations, each with a population of solutions, must be run through the Navier-Stokes solver. Work is continuing to improve this both by optimising the genetic algorithm performance and by considering other optimisation options.

The next phase of the work will apply the method to a complex coastal situation where, it is believed, the model will show the benefits that come from considering entropy as the basis for a solution.

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