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Spatial Discretisation Technology in Coastal Oil Spill Modelling

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Abstract: Spatial discretisation plays an important role in many numerical environmental models. This paper studies the technology of spatial discretisation in coastal oil spill modelling with a view to assure the quality of modelling outputs for given spatial data inputs. Spatial data analysis techniques are effective for investigating and improving the spatial discretisation in different phases of the modelling. Proposed methods are implemented and tested with experimental models. A new “automatic search” method based on GIS zone design principles is shown to significantly improve discretisation of bathymetric data and hydrodynamic modelling outputs. The concepts and methods developed in the study are expected to have general relevance for a range of applications in numerical environmental modelling.

1. Introduction:

The impact of environmental change normally has a spatial dimension. In most environmental simulation modelling, the numerical computation or manipulation has to work with discretised spatial data rather than continuous data or point survey data. Spatial discretisation has therefore been widely used for numerical environmental modelling (e.g. Goodchild *et al.*, 1996; NCGIA, 2000; Brimicombe, 2003). Through spatial discretisation, a tessellation for numerical modelling is established to regroup spatial data to match specific criteria. From this perspective, the discretisation in numerical environmental modelling can be regarded as a zone design issue. However, environmental simulation models show more diversity and complexity in data structures and computation. Modelling could be very different for water quality, air quality, soil pollution, as well as flooding, landslide and soil degradation. Consequently, there are a range of different spatial discretisation procedures in environmental modelling. They raise a

number of interesting issues as well as demand for proper study.

In coastal oil spill modelling, spatial discretisation is the basis for numerical computation and simulation. Discretisation is used to construct the modelling mesh for Finite Element or Finite Differential computation in hydrodynamic modelling. It also generates the modelling grid for trajectory and fate simulations. Current *de facto* industry procedures for such discretisations are pragmatic. However in many cases, such procedures could lack quality control and largely depend on the modeller’s experience. With reference to a number of spatial data analysis techniques, this paper studies the control of spatial discretisation in coastal oil spill modelling with a view to assuring the quality of modelling outputs for given spatial data inputs. The study aims to be generally applicable for different coastal oil spill models regardless to their modelling details. It also expects that such quality control would be easily implemented without spatial data quality expertise.

2. Spatial data analyses for spatial discretisation:

Discretisation in coastal oil spill modelling is a spatial data issue as discussed above. However in many cases, *de facto* industry procedures for such discretisation have not benefited from spatial data analysis and spatial data quality analysis techniques. Such procedures therefore generally lack quality control.

Various zone design methods, as widely-used spatial data analysis techniques, have been successfully developed and implemented for spatial discretisation in numerical modelling (Openshaw & Abrahart, 2000; Openshaw & Rao 1995). In this study, a new approach based on zone design method is developed for the spatial discretisation in hydrodynamic sub-modelling. Spatial discretisation in hydrodynamic sub-modelling has the most impact on coastal oil spill model performance. The new method proposed here aims to improve and assure the quality of such discretisation.

Spatial data quality analyses have been recognised as essential for numerical modelling which involve spatial data and spatial computing (Heuvelink, 1998; Heuvelink et al., 2002). In this paper, spatial data quality tests are used to investigate the model sensitivity and error propagation for different spatial discretisations. It should be noted in this regard that high resolution discretisation (i.e. small cell size) may not assure the high accuracy of model output. Also, if the resolution is too high, the increased computational time may make modelling not feasible. Furthermore, inappropriate discretisations often introduce errors and uncertainties in numerical computation. Through spatial data quality analyses, the data quality can be managed

for spatial discretisation in coastal oil spill modelling.

In this paper, two sets of studies are carried out on different aspects of discretisation for coastal oil spill modelling (Section 3 and 4). They demonstrate the control over spatial discretisations by spatial data analysis and spatial data quality analysis. The first (a preliminary study) considers the effect of grid size on coastal oil spill trajectory sub-modelling and is largely a qualitative analysis of the outputs that nevertheless highlights the importance of appropriate control of the discretisation. The second (a quantitative study) is a more complex set of experiments which tests a new method of discretisation in hydrodynamic sub-modelling compared with the *de facto* industry standard approach.

3. Preliminary study for spatial discretisation in trajectory sub-modelling:

Within the trajectory sub-model, the water area where an oil spill scenario is to be simulated is usually spatially discretised into a grid mesh where each grid cell is a small square. The spilled oil is normally represented by discrete droplets. The number of oil droplets is then assigned as one attribute of the grid cell where an equivalent amount of spilled oil is to be released into the environment. Through spatial discretisation, the oil spill process can then be modelled numerically. The oil droplets can move across the water cells in response to currents, get stuck on the shoreline cells, be stopped by land cells, be lost due to weathering processes or leave the study area by moving across the outer sea boundary.

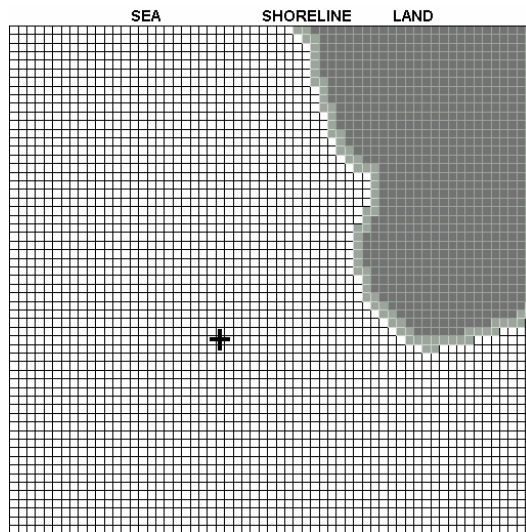


Figure 1 One example of modelling grid for oil spill scenario

The spatial discretisation in the trajectory sub-modelling is affected by various factors such as the scale of oil spill accidents, the area of water under study, the speed of currents, the time step of computation and the geographic features. Although calibration may be undertaken sometimes, the size of grid cell is usually determined subjectively by experience. In this study, the use of sensitivity analysis (Saltelli *et al.*, 2000) was proposed for determining the appropriate cell size with the consideration of oil spill behaviour. In the experiment, the cell size was set at three different levels (100m, 200m and 400m) and trajectory simulations were run on these grids to examine the oil spill behaviour in outputs. In order to preserve experimental simplicity, it has been assumed that all of the oil generated in the spill entered the trajectory model instantaneously at the beginning of the run and at one location. This location is marked as a cross in Figure 1. From progressive experimentation, it was found that for this case the trajectory simulation is sensitive to cell sizes in the range of 100m to 400m (see Figure 2).

Considering the results depicted in terms of the oil spill behaviour, the simulated trajectory on the 400m grid at 0.5 hour has become a linear streak and at 2.5 hour has broken up into a number of widely separated portions (see the third row of Figure 2), both of which do not accord with the observed reality of oil slick behaviour. The 400m discretisation is therefore considered to be too large and hides finer transportation and diffusion processes. Considering the simulated trajectory on the 100m grid (shown in the first row of Figure 2), it doesn't accord well with the observed distribution of oil density in a slick which should be higher at the centre of the slick and gradually decrease to the edge of the slick. On the other hand, inspection of 100m grid at 1.5 hour shows that the slick has become finely scattered rather than remaining as a coherent slick of oil. Such behaviour is not normal observed oil spill behaviour. The reason for these problems arising with the 100m grid is that cell is too small and thus has a tendency to amplify the diffusivity. Considering the trajectory on the 200m grid in Figure 2, it has less of the defaults attributed to the other two: the slick is not scattered and maintains reasonable shape; the density distribution also reflects the observed spreading behaviour of oil slicks. On balance then, the 200m grid is regarded as an appropriate grid size *in this specific case* for simulating the trajectory of the oil spill.

The above experiment shows that this sensitivity test is effective for controlling the spatial discretisation in trajectory sub-modelling. For the same trajectory model, the appropriate size of grid cell may need to be varied according to geographic locations or oil spill scenario. Such tests could be undertaken frequently to assure the quality of model output. The suggested method is obviously practical for such purposes.

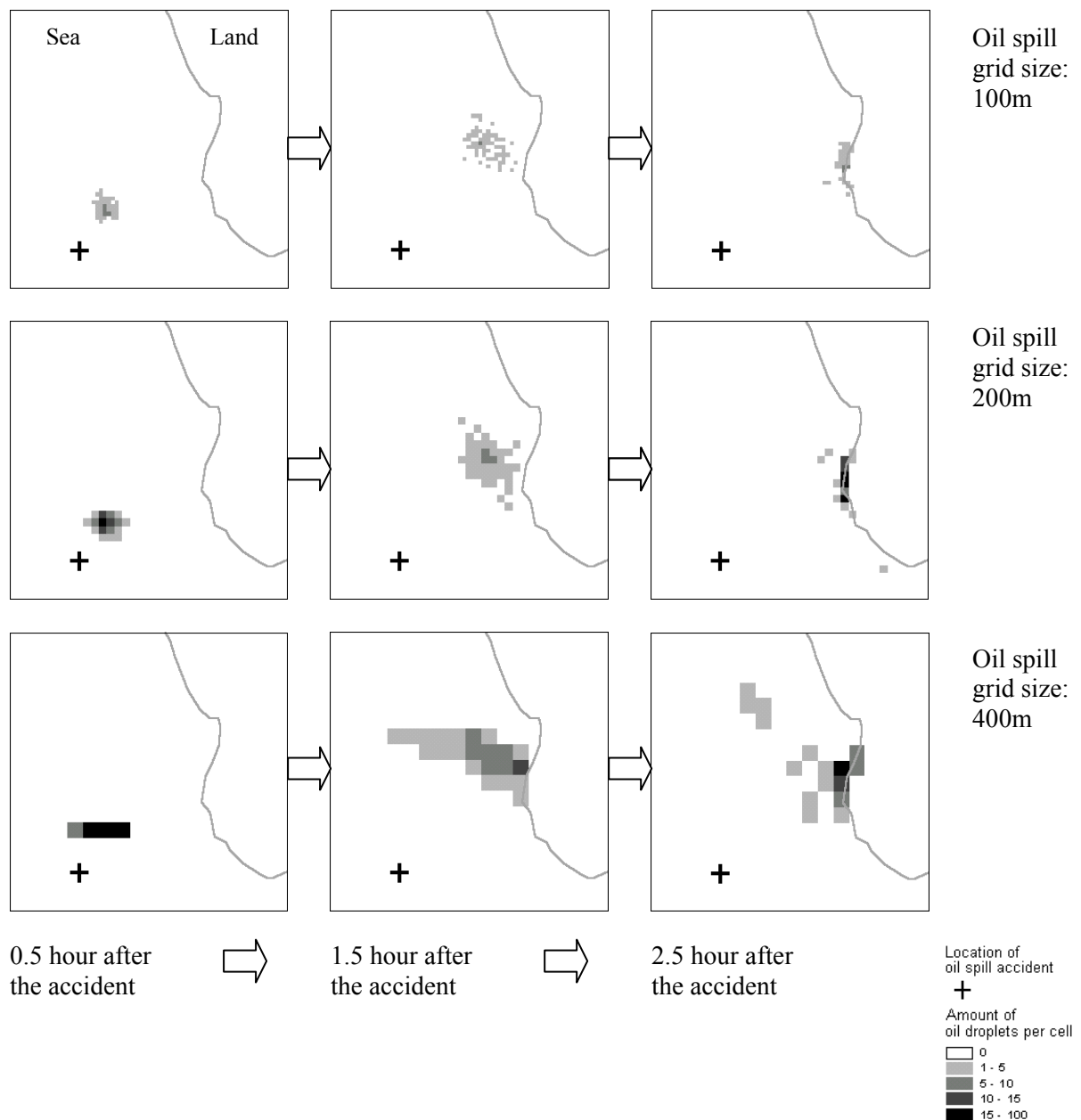


Figure 2 The snapshots for trajectory simulation on 100m / 200m / 400m size modelling grid at 0.5 hour / 1.5 hour / 2.5hour after the accide

4. Quantitative study for spatial discretisation in hydrodynamic sub-modelling:

The hydrodynamic sub-model is essential for any coastal oil spill model, and as being the first stage of modelling, it can have important knock-on impacts on the sub-

models that follow. The hydrodynamic sub-model is also more complex than the other sub-models and is therefore methodologically more challenging. This section presents a quantitative study for controlling the data quality of spatial discretisation for Finite Element

computation in hydrodynamic sub-modelling.

For the experimental hydrodynamic model used in this study, the tidal current simulation, as the model output, has four elements: eastward amplitude (Ua), eastward phase-lag (Ug), northward amplitude (Va), northward phase-lag (Vg). The tidal current can then be represented in the following formula:

$$\begin{aligned} U(x, t) &= Ua \cos(\omega t - Ug) \\ V(x, t) &= Va \cos(\omega t - Vg) \end{aligned} \quad (1)$$

where $U(x,t)$ is the eastward velocity, $V(x,t)$ is the northward velocity, x is the location, t is the time, ω is the angular frequency.

4.1. Discretisation methods:

For numerical computation in hydrodynamic modelling, the bathymetric data need to be discretised into a group of spatial elements. These spatial elements are either triangular or grid according to the computation method used in the modelling: triangular for Finite Element method or grid for Finite Differential method (Foreman, 1990). The size of each element varies over space following the Courant criterion. In hydrodynamic modelling, the Courant criterion will assure the stability and accuracy of numerical computation. The Courant criterion couples the size of spatial element and the time step of numerical computation as follows (Molkenthin, 1996):

$$\Delta t < \Delta x / (|u| + \sqrt{gH}) \quad (2)$$

where Δx is the element size, Δt is the time step of computation, $|u|$ is a global fixed constant for the water body being modelled, g is the acceleration of gravity and H is the water depth at the location of relevant

element. From the point view of spatial data analysis as discussed in the Section 2, such a spatial discretisation is in fact the development of a zonal system. Could GIS-based zone design techniques be employed to improve the quality of discretisation and hence the quality of modelling? In what follows, two discretisation methods are described and compared. One of them is a *de facto* industry standard procedure whilst another one is a new proposed method based on the principles of zone design techniques. The paper starts with the *de facto* industry standard known as “Spiral Search” method which expands each zone through a “Spiral Search” around an initial point. The parameters of Courant criterion will be set and the first point will be chosen. A first zone will be developed to match the Courant criterion and then second zone will be created next to the first one. If a zone has not matched the Courant criterion and has no neighbouring space around for further expansion, it will be abandoned. If a zone has matched the Courant criterion, this zone will be saved. The zone system will grow by repeating such expansion until no space is left in the study area for creating any more zones that match the Courant criterion. In the process of “Spiral Search”, zones created later may have contorted shapes due to the constraint from previously created zones. The geometric centroid of these irregular shapes may not be able to well represent their zones. The triangular modelling mesh, which is subsequently formed using these centroids as delaunay triangulation, may therefore not satisfy the Courant criterion. Also as discussed previously, some zones have to be abandoned if they can’t match the Courant criterion, which then leaves gaps in the study area. However, for Finite Element computation to be effective, the triangular modelling mesh generated from the


centroids of these zones must cover the whole study area.

The second method is new and proposed by this paper as “Automatic Search” method. It is enhanced from existing concept of spatial zone design (Openshaw & Rao 1995; Openshaw 1998). The basic idea of spatial zone design technology is that spatial zonal data can be modifiable due to their nature. This new method is defined here as an “Automatic Search” method. After pre-setting the parameters of Courant criterion, the “automatic search” method firstly expands a zone as a circle around an initial point with the condition of matching the criterion. The sequential zones will be created in the same way. If some of these zones can't match the Courant criterion and have no room to be expanded, they will be abandoned. This process will be carried out until there is no unprocessed area left. Being different from the “Spiral Search” method, a zone modification process is introduced as a second stage in the “Automatic Search” method. In this second stage, each zone is modified with the Courant criterion. The modification includes enlarging the zones, shrinking the zones or loosening the criteria. The zones can be enlarged as a circle or can grab the uncovered space next to it. If the zones need further expansion and have no space around, their neighbouring zones can also give up the space to them given the Courant criterion will not be violated. If there are still uncovered space (i.e. gap) after all these processes, the criteria could be loosened and the modification can be carried on further. The modification process is repeated until the whole study area is covered. This new method is designed to produce a complete and relatively regular zone system, which can then lead to a triangular modelling mesh for matching the Courant criterion and could have a sounder

basis for numerical hydrodynamic modelling.

4.2. Experiment and analysis:

The experiment was designed for comparing and testing the two different discretisation methods: “Spiral Search” and “Automatic Search” methods. Synthetic bathymetric data were used in both experiments for excising control over the systematic testing and to provide a baseline to test the effects of spatial discretisation (i.e. the zone system).

The seabed used in this experiment combines both convex and concave forms, also includes a channel and a ridge (Figure 3). The spatial extent of the study area is 20km × 40km, and its water depth is 0m - 50m. Although the bathymetric input is more complex than the previous experiment, similar results can be seen in the zone systems created by the spatial discretisation methods. Figure 4(a) shows the zone system generated from the “Spiral Search” method. There are 79 zones and 12 gaps, where gaps are shown as . The zone system created by using the new “Automatic Search” method has 71 zones (Figure 4(b)). Consistent with the results shown in the first experiment, no gap has been left in the study area after the process. Comparing with the zone system (Figure 4(a)) formed by “Spiral Search” method, there are considerable less contorted zones in the zone system (Figure 4(b)) created by “automatic search” method. At the next stage of the experiment, triangular meshes were created from both zone systems and the hydrodynamic model was run on these derived triangular meshes. Analysis on the residual errors propagated from both zone systems were also carried out, and the results are given in Table 1. In this experiment, both phase-lag elements Ug and Vg (eastward phase-lag and northward

phase-lag) are sensitive to spatial discretisation. As mean values of the residual errors are very small in this case, only standard deviations value (STDEV) of the residual errors was used to compare the differences between the two methods. For elements Ug and Vg , the STDEV value of the residual error propagated from the zone system created by “Automatic Search” method is smaller than the ones by “Spiral Search” method (see the second and fourth columns in Table 1). The errors for other elements (Ua and Va) of tidal current simulation are very small. T-test was carried out for these two sets of residual errors in Vg and Ug generated by using the two different methods “Spiral Search” and “Automatic Search”. The T-test results show that there is a significant difference for STDEV at $p < 0.05$.

From the results of above experiment, the proposed “Automatic Search” method has improved the zone systems discretised from the bathymetric data in hydrodynamic modelling. The quality of the model output was shown to have enhanced. The results demonstrate that it is feasible to control the spatial discretisation through zone design technology.

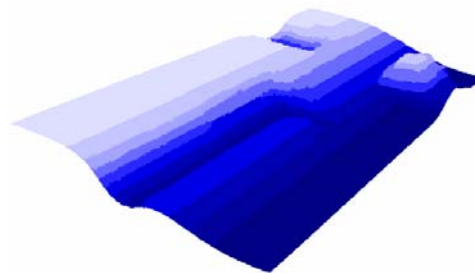


Figure 3 A relative complex bathymetric input: a seabed with convex, concave, a channel and a bridge

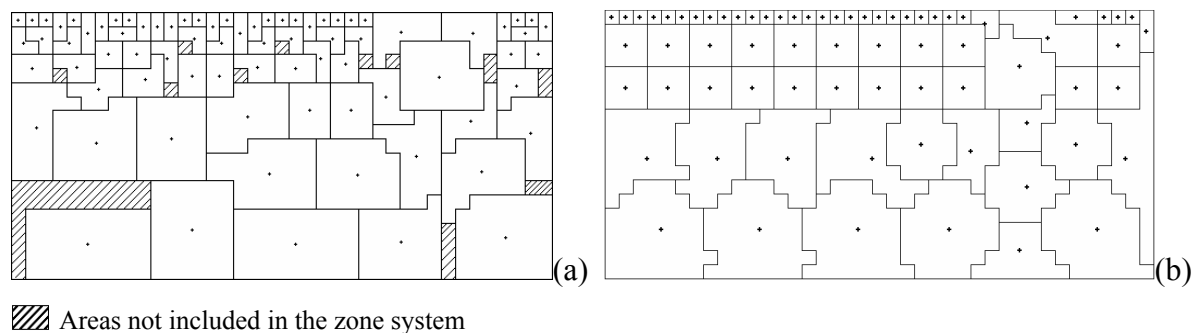


Figure 4 Different zone systems for spatial discretisation (complex bathymetric input): (a) zone system from “spiral search” method; (b) zone system from “automatic search” method

Table 1 The residual errors in tidal current simulations propagated from the two zone design methods (complex bathymetric input)

Tidal current elements	<i>Spiral Search Method</i>		<i>Automatic Search Method</i>	
	Mean	STDEV	Mean	STDEV
Ua (m/s)	0.10	0.08	0.10	0.08
Ug (radian)	0.02	1.39	0.08	1.29
Va (m/s)	0.12	0.09	0.12	0.09
Vg (radian)	0.18	1.29	0.16	1.11

5. Conclusions:

This paper has demonstrated that spatial discretisation is critical for coastal oil spill modelling. Control of spatial discretisation would assure the reliability of simulations, improve the quality of model outputs and reduce uncertainty in subsequent decision-making. The paper has also shown that spatial data analysis techniques are effective for controlling the spatial discretisation in coastal oil spill modelling. Initial methods have been developed for investigating and improving the spatial discretisation with the experimental models, which can be easily implemented by modellers without spatial data quality expertise.

In a broad sense, control of spatial discretisation is also essential for a wide range of environmental simulation models. The concepts and methods developed in this study are therefore expected to have general relevance for a range of applications in numerical environmental modelling.

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