Oil spill modeling using 3D cellular automata for coastal waters

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Oil Spill Modeling Using 3D Cellular Automata for Coastal Waters

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ABSTRACT

Oil spill accident is very harmful to the coastal and marine ecology and mankind. The simulation and prediction of the transport and fade of spilled oil is one of the important issues to the oil spill contingency plans.
Cellular Automata (CA) is one of the dynamic modeling tools easy to use. It usually divides the space into regular grid cells in 2D or 3D. And transformation functions according to physical, chemical and biological phenomena are set to define the dynamic process between local neighboring cells. Because the data structure of CA is very similar to the raster data model in the Geographic Information Systems (GIS), the CA model can be easily integrated with GIS to provide environmental database and to display the simulation results. The algorithm of a 3D CA model can be straightforwardly extended from those of 2D CA model.
This paper used 3D CA model to simulate the spreading, evaporation, advection due to wind and current on the water surface, evaporation, shoreline deposition with islands and shorelines. The horizontal and vertical dispersion, advection in the water column and seabed sedimentation were also modeled by this 3D CA approach. Conservation of mass and many physical oil transport rules were used in the prediction model.
Several simulation cases were applied in the area of 10km * 10km. The horizontal grids are divided into 100*100. And 5 layers in the water column are used in the maximum water depth of 50m. Islands, shorelines and water depth are also included in the simulation cases. It is proved 3D CA model is a capable and efficient way to simulate and predict the movement of the oil slick.

KEY WORDS: Cellular automata; oil spill; Geographic Information Systems; spreading; advection; shoreline deposition; horizontal and vertical dispersion

INTRODUCTION

Because oil spill accidents happened very often in the last decades, the related tasks, such as: oil spill monitoring, prediction and management, became very important issues. Marine ecology will be impacted by the oil spill incident. Oil slick may be mixed with sea water and sink toward sea bottom in the water column. Ecological environment of the sea bottom may be affected by the sunken oil. Coast will be polluted and hard to clean if oil slick floats to the land. Contingency plans should be initiated as soon as oil spill accident happened. Oil dispersion model can predict the dynamic behavior and the distribution of the oil slick according to the local ocean current, wave and other environmental conditions. Suitable action then can be made by the decision makers with the results from this prediction. Therefore, study of the dynamic behavior of the oil spill is one of the key issues in the emergency response decision support systems.
Lab test and analytical approaches can be used to predict the dynamic behavior of the oil spill (Okuyama et al., 1988; Cekirge et al., 1990; Karpen and Galt, 1979). However, it is too hard for the lab test and analytical methods to consider all the environmental factors, such as: wind, ocean current, tidal current, turbulence, wave, evaporation, shoreline deposition etc., in simulation processes. Wang et al. (2005), Pierre (1996) and Sebastiao et al. (1995) had put wind and ocean current into their numerical model. Riazi et al. (1999) added more factors, such as: evaporation, dissolution, settlement, into his numerical model. Shaw (2003) had considered the impact of the wave to the oil slick. Thorpe (2000) had investigated the behavior of the oil dispersion in the shallow water. Oil slick mass in the water surface will be broken into particles by wave and mixed with sea water. Part of the oil particles will float to water surface and mixed with floating oil again. At the same time, rest of the oil particles will sink toward sea bottom. We can tell that behavior of the oil spill is a three dimensional dispersion process (Korotenko, 2000). Oil slick particles can be measurable up to water depth of 20 meters (Cretney et al., 1981; Sorstrom, 1987; Genders, 1988). It is hard to include many environmental factors in the numerical models at a time. And three-dimension model is even harder to establish.
Cellular Automata (CA) is one of the dynamic modeling tools easy to build in 2D or 3D environments and convenient to add many environmental factors, such as: shoreline boundary, wind, current, evaporation etc., in the model. Adding vertical dispersion and advection factors to the CA model, oil spill behavior prediction in 3D can be simulated more realistic.
Because the data structure of CA is very similar to the raster data model

of the Geographic Information Systems (GIS), the CA model can be easily integrated with GIS to provide environmental database and to display the simulation results. The algorithm of a 3D CA model can be straightforwardly extended from those of 2D CA model.

CELLULAR AUTOMATA (CA)

CA consists of an infinite, regular discrete grid of cells, each in one of a finite number of states. The grid can be in any finite number of dimensions. Time is also discrete, and the state of a cell at time t is a function of the states of a finite number of cells (called its neighborhood) at time t-1. These neighbors are a selection of cells relative to the specified cell, and do not change. Every cell has the same rule for updating, based on the values in this neighborhood. Each time the rules are applied to the whole grid a new generation is created (Wikipedia, 2007).

The basic units for composing a CA include: cell, state, lattice, neighbor, rule, and time. Cell can be a square, triangle, or hexagonal grid. Lattice is formed by any one type of grid with definite boundary in one, two or higher dimension. Types of the boundary can be periodic, reflective or constant. State can be in binary form or a value. Usually each cell has only one state at a time. Neighbor can be four cells on the principle directions or eight cells around a specific cell in two dimensional CA. Transferring from current state to the next, we should set up a definite transition rule in advance according to current state of a specific cell and the state of its neighbors. Time and time step is discrete and usually an integer.

OIL SPILL MODELING BY CA

Oil spill modeling includes physical, chemical, biological processes. This paper used 3D CA model to simulate the spreading, evaporation, advection due to wind and current, evaporation, shoreline deposition on the water surface. The horizontal and vertical dispersion, advection in the water column and seabed sedimentation were also modeled by this 3D CA approach. Conservation of mass and many physical oil transport rules were used in the prediction model. CA for oil spill modeling includes simulation of water surface transport and water column transport.

WATER SURFACE TRANSPORT FOR CA

In water surface, oil slick spreading is related to the oil mass, water surface tension force, inertia and viscous force etc. Wind and water current may cause oil slick in the water surface to have horizontal movement. Mass of the oil slick in the water surface may decrease due to interaction with air and evaporation depending on the properties of the oil slick. Oil slick mass may be broken into particles by wave and sink down to water column. As long as oil slick is transported to the land, shoreline deposition will be happened. We should consider all of the factors mentioned above for water surface transport in CA.

1. Spreading without wind and current:

Area of the oil slick will be changed due to imbalance between internal and external forces to the oil slick (eg. gravity force, inertia, viscous force and surface tension force etc.) under no wind and no current condition. Cell with larger oil mass will flow to cell with smaller mass. The spreading without wind and water surface current in CA can be described as follows (Karafyllidis, 1997):

In figure 1, the oil mass in cell (i,j) with its neighbor cell (i-1,j) can be formulated as:

$$M^{t+1}_{i,j}=M^t_{i,j}+m(M^t_{i-1,j} - M^t_{i,j}) \qquad (1)$$

where $M^{t+1}_{i,j}$ is the oil mass in cell (i,j) at time t+1,
$M^t_{i,j}$ is the oil mass in cell (i,j) at time t,
$M^t_{i-1,j}$ is the oil mass in cell (i-1,j) at time t,
m is spreading constant in water surface,

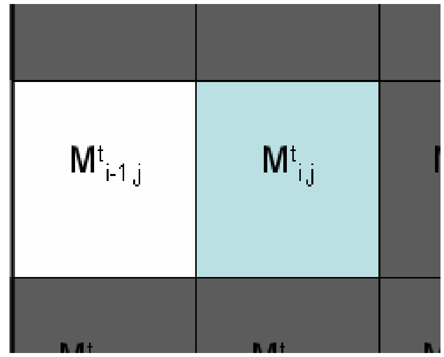

Fig. 1 cell (i,j) and its neighboring cell (i-1,j)

The spreading in four diagonal cells (NE, SE, NW, SW) of a specific cell are smaller than spreading in four cells on the principle directions (E, W, S, N), therefore, spreading constant in four diagonal cells d will be added. In figure 2, the oil mass in cell (i,j) with its neighbor cell (i-1,j+1) can be formulated as:

$$M^{t+1}_{i,j}=M^t_{i,j}+m[d(M^t_{i-1,j+1}-M^t_{i,j})] \qquad (2)$$

where $M^{t+1}_{i,j}$ is the oil mass in cell (i,j) at time t+1,
$M^t_{i,j}$ is the oil mass in cell (i,j) at time t,
$M^t_{i-1,j+1}$ is the oil mass in cell (i-1,j+1) at time t,
m is spreading constant in four cells on the principle directions in water surface,
d is spreading constant in four diagonal cells in water surface,

After summarizing spreading from eight neighboring directions for cell (i,j), the oil mass in cell (i,j) at time t+1 can be formulated as:

$$M^{t+1}_{i,j}=M^t_{i,j}+\{m[(M^t_{i-1,j}-M^t_{i,j})+(M^t_{i+1,j}-M^t_{i,j})+(M^t_{i,j+1}-M^t_{i,j})+(M^t_{i,j-1}-M^t_{i,j})]\} + \{md[(M^t_{i-1,j+1}-M^t_{i,j})+(M^t_{i-1,j-1}-M^t_{i,j})+(M^t_{i+1,j+1}-M^t_{i,j})+(M^t_{i+1,j-1}-M^t_{i,j})]\}\} \qquad (3)$$

Because m and d may affect the spreading in the specific cell, and mass of transporting out from the specific cell should be less than total mass of the specific cell. That is the relationship between m and d is (m+md<=0.25).

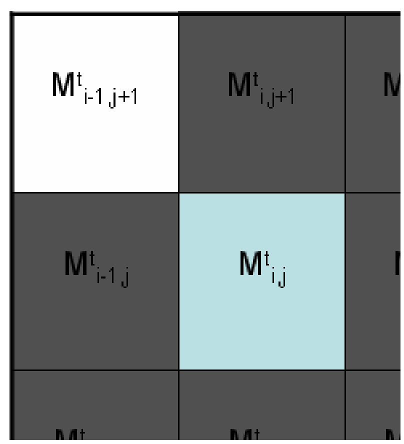

Fig. 2 cell (i,j) and its neighboring cell (i-1,j+1)

The value of m and d should be determined by the experiment. The shape of spreading under no wind and no current is near a circle. According to the result from the study of Karafyllidis (1997), the shape of spreading is close to a circle if d value is equal to 0.18. According to experience, m value can be assumed as 0.098.

2. Evaporation

Evaporation will happen right after oil spill. The rate of evaporation depends on the percentage of the volatile materials in the oil slick and the temperature of the environment (Reijnhart and Rose, 1982). The addition term in CA for evaporation is $–pt_mT^t$, where p is a constant of evaporation rate and unit is $[kg(secK)^{-1}]$, t_m is the time step in second, and T^t is the temperature of the environment at time t and unit is degree of K.

3. Advection due to water current and wind driven current

Water current and wind driven current may cause oil slick to move horizontally. If there are no wind and no water current, and the oil mass in cell (i-1,j) is larger than cell (i,j) at time t, then oil slick will move from west to east. Spreading with wind driven current or water current from west cell can be formulated as:

$$M^{t+1}_{i,j}=M^t_{i,j}+m\{[(1+ W^t_{i,j})M^t_{i-1,j}-(1- W^t_{i,j})M^t_{i,j}]\} \quad (4)$$

Where $M^{t+1}_{i,j}$ is oil mass in cell (i,j) at time t+1,

$W^t_{i,j}$ is the correction factor for wind driven current or water current from western cell of cell (i,j) at time t

If there exists wind driven current or water current from western cell, the correction factor $W^t_{i,j}$ for them in cell (i,j) at time t can be formulated as:

$$W^t_{i,j}=WW^t_{i,j}+WC^t_{i,j} \quad (5)$$

$$WW^t_{i,j} = R_w * [(WVW^t_{i,j} + WVW^t_{i-1,j})/2/ WV_{max}] \quad (6)$$

$$WC^t_{i,j} = [(CVW^t_{i,j} +CVW^t_{i-1,j})/2/ CV_{max}] \quad (7)$$

where R_w is a constant which transforms from wind speed to wind driven current speed, and its value varies between 0.03 and 0.16 (Phillips and Groseva, 1977),

$WW^t_{i,j}$ is correction factor for wind driven current from western cell of cell (i,j) at time t,

$WVW^t_{i,j}$ is wind speed projected in west component in cell (i,j) at time t,

$WVW^t_{i-1,j}$ is wind speed projected in west component in cell (i-1,j) at time t,

WV_{max} is the maximum observed wind speed,

$WC^t_{i,j}$ is correction factor for water current from western cell of cell (i,j) at time t,

$CVW^t_{i,j}$ is water current speed projected in west component in cell (i,j) at time t,

$CVW^t_{i-1,j}$ is water current speed projected in west component in cell (i-1,j) at time t,

CV_{max} is the maximum observed water current speed,

4. Shoreline Deposition

When oil slick floats to the land, part of oil slick will deposit along the beach. However, oil slick carrying capacity of the beach is not unlimited. According to the study of Humphrey et al. (1993), maximum oil slick carrying capacity of the beach is $C_{max}=L_sW_sD_sN_{eff}$, where L_s, W_s and D_s are the length, width, and depth of the sediment on the beach, where N_{eff} is the effective porosity of the sediments on the beach and its value varies between 0.12 and 0.46.

In order to simulate the shoreline deposition, special transition rule should be applied in CA if the neighboring cell of a specific cell is land. Mass of shoreline deposition can be formulated as: ${M_{sd}}^t_{i,j}=P_{sd}M^t_{i,j}$, where ${M_{sd}}^t_{i,j}$ is the mass of oil slick transported to beach, where P_{sd} is the coefficient of oil slick transported to beach and value is between 0 and 1, where $M^t_{i,j}$ is the oil mass in cell (i,j) at time t. As long as land cell reaches its oil carrying capacity, oil slick will not allow transporting from sea cell to land cell.

VERTICAL DISPERSION

Oil slick mass may be broken into particles by breaking wave and upper water surface turbulence. Oil slick particles may be transported toward sea bottom. It is called vertical dispersion. This is one of the reasons why mass of oil slick on the water surface may be decreased. Delvigne and Sweeney (1989) and Delvigne (1994) conducted a series of laboratory investigations to detect the relationship among oil entrainment rate, particle size and intrusion depth of oil particles. They described the entrainment rate as a function of the oil type, breaking-wave energy and wind speed. Their study showed that entrainment rate of oil particles is proportion to 1.14 root of the RMS wave height. However, we didn't include wave height as one of the factors in CA. Therefore, we regarded the RMS wave height in the whole area as a constant. The major factors we considered in vertical dispersion are oil type and wind speed in CA model. The vertical dispersion can be formulated as:

${M_{svd}}^t_{i,j}=RsVw^t_{i,j}M^t_{i,j}$, where ${M_{svd}}^t_{i,j}$ is vertical transported mass in cell (i,j) at time t, where Rs is the vertical dispersion rate of a specific oil type on the water surface, where $Vw^t_{i,j}$ is the relative wind speed, where $M^t_{i,j}$ is the oil mass in cell (i,j) at time t. Relative wind speed can be calculated as $Vw^t_{i,j}=W^t_{i,j}/WV_{max}$, where $Vw^t_{i,j}$ is relative wind speed in cell (i,j) at time t, where $W^t_{i,j}$ is the wind speed in cell (i,j) at time t, where WV_{max} is observed maximum wind speed. The value of Rs is between 0 and 1. In our study, Rs was regarded as 0.0001 according to experience.

In order to simulate the vertical dispersion for oil slick close to land, we assumed that oil slick will stay in the same cell (i,j) if the cell vertically below this cell is the sea bottom or land.

UNDERWATER TRANSPORT FOR CA

In the dispersion process of the oil slick, there are three typical layers in water. Surface layer has the floating oil. Water column layer has oil slick particles mixed with water. Sea bottom layer has heavier oil slick which may always stay or deposit at bottom layer. The oil slick at different layer may be moved upward or downward when vertical dispersion happened. Because the shape of oil slick is irregular, this causes the drag forces in each parts of oil particles differently during vertical dispersion process. This is one of the reasons why oil slick may move horizontally in the water column. The oil slick in the water column may also move horizontally if there exists current in the water column. We should consider these factors in the vertical transport process of oil slick.

1. Horizontal dispersion due to drag forces in the water

This process is similar to the horizontal dispersion in the water surface, except m_w and d_w are different. It may be formulated as:

$$M^{t+1}_{i,j} = M^t_{i,j} + \{m_w[(M^t_{i-1,j} - M^t_{i,j}) + (M^t_{i+1,j} - M^t_{i,j}) + (M^t_{i,j+1} - M^t_{i,j}) + (M^t_{i,j-1} - M^t_{i,j})]\} + \{m_wd_w[(M^t_{i-1,j+1} - M^t_{i,j}) + (M^t_{i-1,j-1} - M^t_{i,j}) + (M^t_{i+1,j+1} -M^t_{i,j}) + (M^t_{i+1,j-1} - M^t_{i,j})]\} \quad (8)$$

where $M^{t+1}_{i,j}$ is the oil mass in cell (i,j) at time t+1, where $M^t_{i,j}$, $M^t_{i,j+1}$, $M^t_{i,j-1}$, $M^t_{i-1,j}$, $M^t_{i+1,j}$, $M^t_{i-1,j+1}$, $M^t_{i-1,j-1}$, $M^t_{i+1,j+1}$, $M^t_{i+1,j-1}$ are the oil mass in cell (i,j) and its eight neighboring cells at time t, where m_w and d_w are spreading constant in four cells on the principle directions and in four diagonal cells in the water column.

2. Advection due to current in the water column

The advection due to current and horizontal dispersion in the water column can be formulated as:

$$M^{t+1}_{i,j}=M^{t}_{i,j}+\{m_w[((1+W^{t}_{i,j})\ M^{t}_{i-1,j}-(1-W^{t}_{i,j})\ M^{t}_{i,j})+((1+E^{t}_{i,j})M^{t}_{i+1,j}-(1-E^{t}_{i,j})M^{t}_{i,j})+((1+N^{t}_{i,j})M^{t}_{i,j+1}-(1-N^{t}_{i,j})\ M^{t}_{i,j})+((1+S^{t}_{i,j})\ M^{t}_{i,j-1}-(1-S^{t}_{i,j})\ M^{t}_{i,j})]\}+\{m_w d_w[((1+NW^{t}_{i,j})\ M^{t}_{i-1,j+1}-(1-NW^{t}_{i,j})\ M^{t}_{i,j})+((1+SW^{t}_{i,j})\ M^{t}_{i-1,j-1}-(1-SW^{t}_{i,j})M^{t}_{i,j})+((1+SE^{t}_{i,j})M^{t}_{i+1,j+1}\ (1-SE^{t}_{i,j})\ M^{t}_{i,j})+((1+NE^{t}_{i,j})M^{t}_{i+1,j-1}-(1-NE^{t}_{i,j})\ M^{t}_{i,j})]\} \tag{9}$$

Where $M^{t+1}_{i,j}$ is the oil mass in cell (i,j) at time t+1, where $W^{t}_{i,j}$, $E^{t}_{i,j}$, $N^{t}_{i,j}$, $S^{t}_{i,j}$, $SW^{t}_{i,j}$, $SE^{t}_{i,j}$, $NW^{t}_{i,j}$, $NE^{t}_{i,j}$ are the correction factors for wind driven current or water current from western, eastern, northern, southern, southwestern, southeastern, northwestern and northeastern cells of cell (i,j) at time t in the water column.

$W^{t}_{i,j}$ can be calculated as follows, and rest of the direction components can be computed similarly.

$$W^{t}_{i,j}= WC^{t}_{i,j}$$

$$WC^{t}_{i,j} = (CVW^{t}_{i,j} +CVW^{t}_{i-1,j})/ CV_{max}$$

where $WC^{t}_{i,j}$ is the correction factor for western cell of cell (i,j) at time t in the water column, where $CVW^{t}_{i,j}$ and $CVW^{t}_{i-1,j}$ are the water current speed projected in west component in the cell (i,j) and (i-1,j) at time t in the water column, where CV_{max} is the maximum observed water current speed in the water column.

3. Vertical dispersion due to gravity in the water column

Buoyancy and gravity are the two vertical drag forces applied in the oil after simplification in the water column. The vertical transport of the oil particles is the resultant force of the buoyancy and gravity. In this study, we will only simulate the condition that gravity is larger than buoyancy. In this case, oil particles will sink down. The vertical transport due to gravity can be formulated as: $M_{wvd}{}^{t}_{i,j}=Rw*M^{t}_{i,j}$, where $M_{wvd}{}^{t}_{i,j}$ is oil mass of vertical transport in cell (i,j) at time t, Rw is the vertical dispersion rate of a specific oil type in the water column, $M^{t}_{i,j}$ is oil mass in cell (i,j) at time t.

4. Sedimentation of Seabed Edge

The oil may deposit to the seabed as long as oil sink down to the sea bottom. However, oil may also move horizontally around seabed depending on the roughness and terrain change of the seabed, geological property of the seabed, and the horizontal current around seabed etc. In this study, we assume that oil around the seabed will not deposit to the sea bottom and will move freely in horizontal direction.

EXPERIMENT DESIGN

In our CA experiment for modeling dynamic behavior of the oil spill, several types of cell arrays should be input in advance, (a) 3D cell array for oil mass: record oil mass of each cell at each time step, (b) 3D cell array for bathymetry: record the water depth of each cell, (c) 2D cell array for temperature of environment: record the temperature of environment of each cell at each time step, (d) 2D cell array for wind direction: record the wind direction of each cell at each time step, (e) 2D cell array for relative wind speed: record the relative wind speed of each cell at each time step, (f) 3D cell array for water current direction: record the water current direction of each cell at each time step, (g) 3D cell array for relative water current speed: record the relative water current speed of each cell at each time step.

Regular square grid was used for lattice in our CA model. The resolution of X and Y axis in horizontal direction is assumed the same. The resolution of Z axis in vertical direction is assumed lower than that of horizontal direction.

The state of the cell depends on the type of cell array, (a) cell array for oil mass: value of oil mass is between 0 and +3.402823E+38 with unit of kg, (b) cell array for bathymetry: land cell will be flagged as 1 and ocean cell flagged as 0 without unit, (c) cell array for temperature of environment: value of temperature is between 272 and 325 with unit of K degrees, (d) cell array for wind direction: value of wind azimuth angle is between 0 and 359 with unit of degree, (e) cell array for relative wind speed: value of relative wind speed is absolute wind speed divided by maximum observed wind speed, and value is between 0 and 1 without unit, (f) cell array for water current direction: same with (d), (g) cell array for relative water current speed: value of relative water current speed is absolute water current speed divided by maximum observed water current speed, and value is between 0 and 1 without unit.

Boundary condition will be set depending on types of cell array. Except cell array for oil mass is set as constant boundary, rest of the cell arrays are set as reflective boundary.

CASES STUDY FOR MODELING DYNAMIC BEHAVIOR OF THE OIL SPILL

In the CA experiment, an area of 10 km by 10 km is divided into 100 grids by 100 grids. Maximum depth is set to 50 m and depth is equally divided into 5 layers. Layer 0 has water depth of 0-10m, and layer 1 has water depth of 10-20m, and layer 2 has water depth of 20-30m, and layer 3 has water depth of 30-40m, and layer 4 has water depth of 40-50m. Therefore, the resolution of volume element (voxel) is 100 m by 100 m by 10 m. A time step is set to 10 minutes. The initial mass of spill oil was assumed to be 150 tons of marine fuel oil and distributed in an area of 3 km by 3 km following Gaussian distribution.

Case 1: 2D spreading without wind and current

It assumed spreading constant in four cells on the principle directions (m)=0.098, spreading constant in four diagonal cells (d)=0.18, constant of evaporation rate (p)=0, effective porosity of the sediments on the beach (N_{eff})=0.3, coefficient of oil slick transported to beach (P_{sd})=0. From figure 3 and 4, we know the diameter changed from 3km to 8km after 10,000 minutes (7 days) or time step t=1000 with 150 tons of marine fuel oil spill from the center cell. After calculating total oil mass at time 0 and 2,500 minutes, we found they are equal. That means they had fulfilled law of conservation of energy.

Case 2: 2D dispersion with northern water current on a strip of cells and an island

The simulation condition were similar to case 1, except with northward water current on a strip of cells (refer to figure 5) and an island, and coefficient of oil slick transported to beach (P_{sd})=0.15, and relative northern current speed on strip of cells $WC^{t}_{i,j}$=0.5, and relative eastern wind speed of the whole area $WW^{t}_{i,j}$=1.

From figure 6 and 7, we know that oil in the area with a strip of water current will transport to north after 10,000 minutes or time step t=1000 with 150 tons of marine fuel oil spill from the center cell. Because wind driven current is assumed only 3% of the water current, therefore, the oil mainly floated to north direction. Shoreline deposition did happen in this case.

Case 3: simulate 3D CA with complex bathymetry

The 3D seabed terrain is shown in figure 8. We assumed the water current condition on the surface and in the water column were different in the simulation. It assumed water current at depth of 0-20m was northeastern with relative speed=1, and water current at depth of 20-50m was northwestern with relative speed=1, and relative eastern wind speed=1, and spreading constant in four cells on the principle directions on the water surface (m)=0.098, and spreading constant in four diagonal cells on the water surface (d)=0.18, (p)=0, (N_{eff})=0.3, (P_{sd})=0.15, and vertical dispersion rate of oil on the water surface (Rs)=0.01, and spreading constant in four cells on the principle directions in the water m_w = 0.098, and spreading constant in four diagonal cells in the water d_w=0.18, and vertical dispersion rate of oil in the water column (Rw)=0.01.

Simulation results for layer 0 (water depth 0-10m) can refer to figure 9 and 10, we know that oil on the surface will float to northeastern after 2,500 minutes (41 hours) or time step t=250 and part of the spill oil will deposit on the beach of island. Simulation results for layer 1 (water depth 10-20m) can refer to figure 11 and 12. Layer 1 has similar result with layer 0. Simulation results for layer 2 (water depth 20-30m) can refer to figure 13 and 14. Simulation results for layer 3 (water depth 30-40m) can refer to figure 15 and 16. And figure 17 is for layer 4 (water depth 40-50m) at any time step with no oil in this layer. Because we assumed oil will not stay at the seabed bottom. From figure 13 to 16, we knew that part of the spill oil sank down toward seabed and move horizontally toward north and northwestern in the water column.

CONCLUSIONS

This study had successfully establishing a 3D cellular automata (CA) for simulating and displaying dynamic behavior of the oil spill horizontally and vertically. Environmental factors, such as: spreading, evaporation, current and wind in water surface and underwater, shoreline deposition, horizontal and vertical dispersion, underwater advection, sedimentation, had been used for oil spill simulation in CA. The formula for modeling environmental factors is straightforward and easy to understand. And the data structure of CA is same with Geographic Information Systems (GIS), therefore, the CA can integrate with GIS database and simulation result from CA can be output to GIS without too much effort. CA and GIS integrated system can be a good decision support tools for oil spill contingency plan and emergency response. From results of several CA simulation case, it is proved that 3D CA model is a capable and efficient way to simulate and predict the movement of the oil slick.

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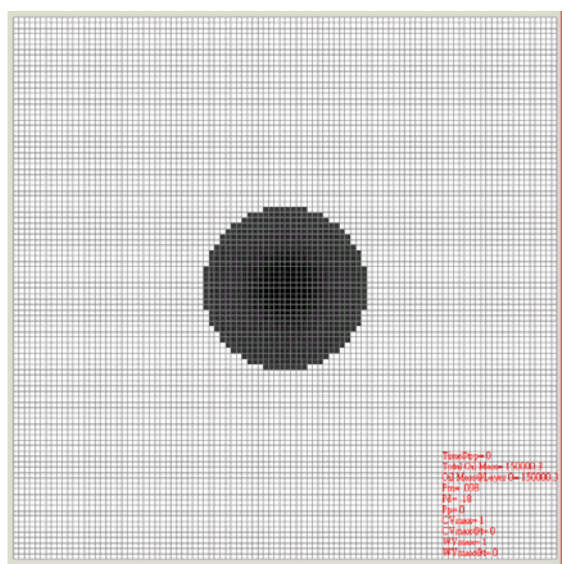

Fig. 3 Case 1 at time step tm=0

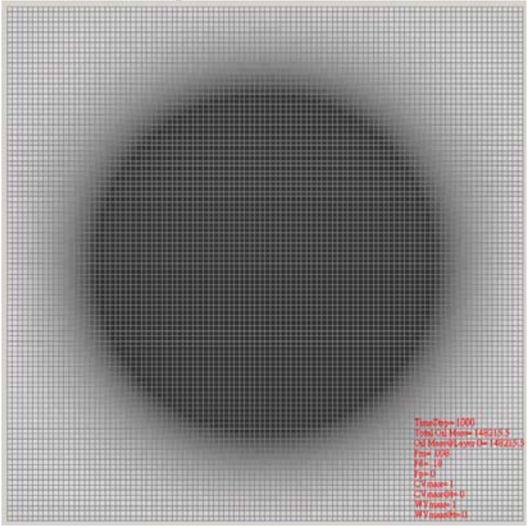

Fig. 4 Case 1 at time step tm=1000

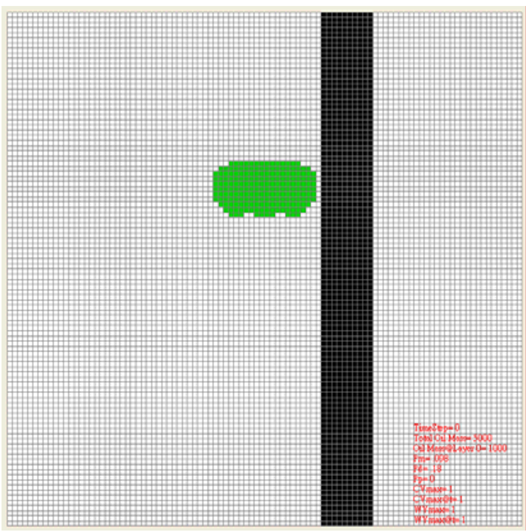

Fig. 5 Strip northward current and an island in Case 2

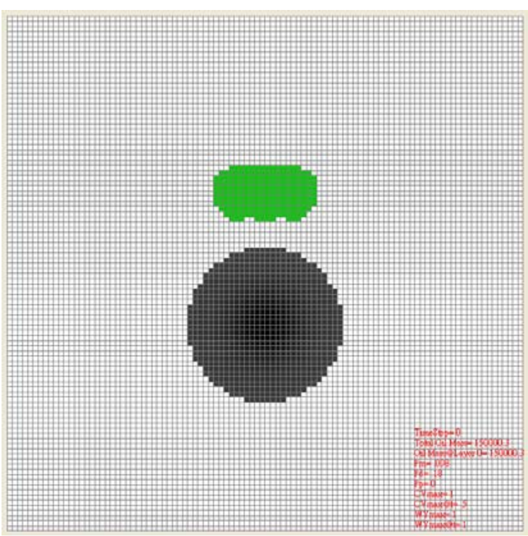

Fig. 6 Case 2 at time step tm=0

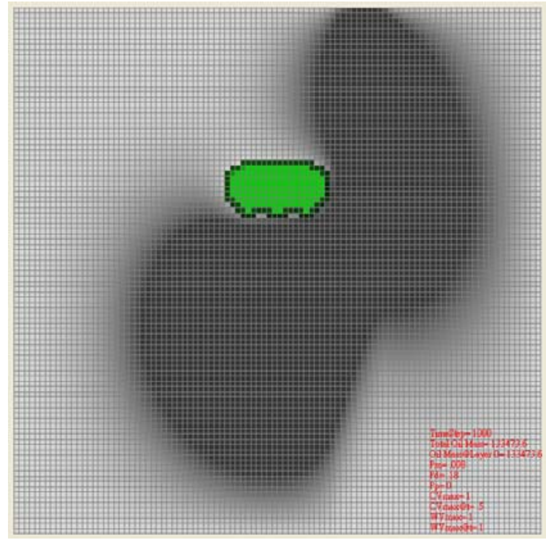

Fig. 7 Case 2 at time step tm=1000

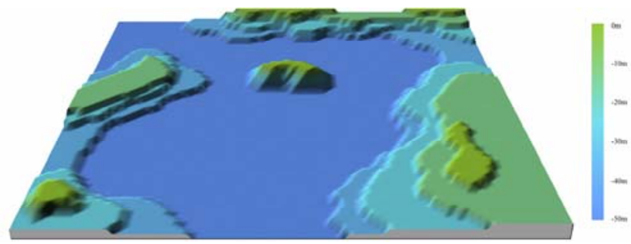

Fig. 8 3D Seabed Terrain for Case 3

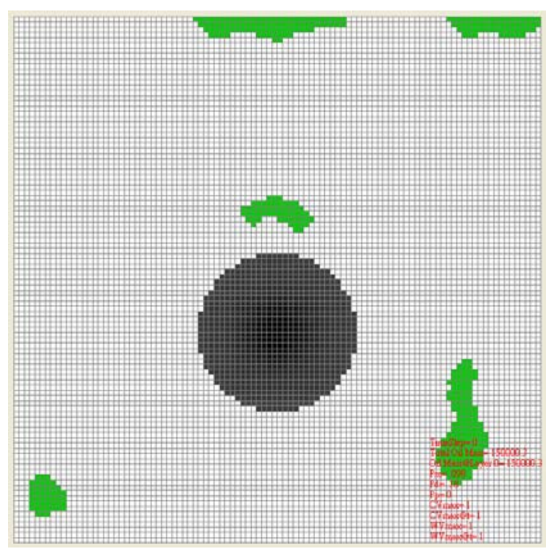

Fig. 9 Case 3 at time step tm=0 at layer 0

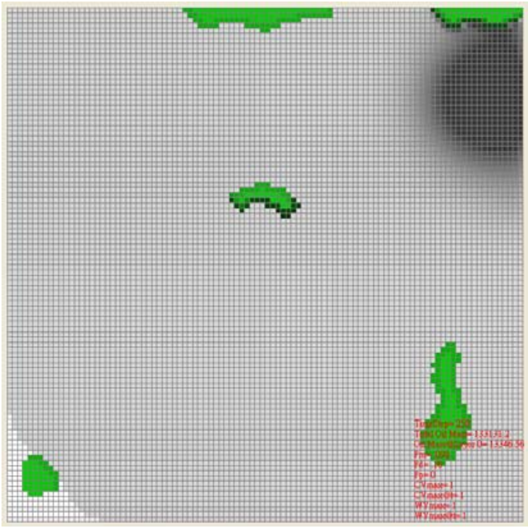
Fig. 10 Case 3 at time step tm=250 at Layer 0

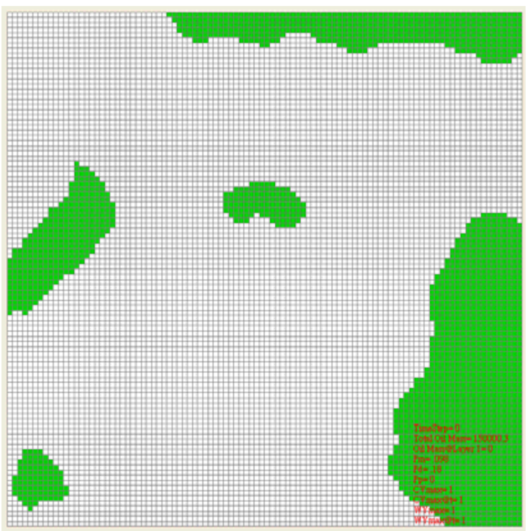
Fig. 11 Case 3 at time step tm=0 at layer 1

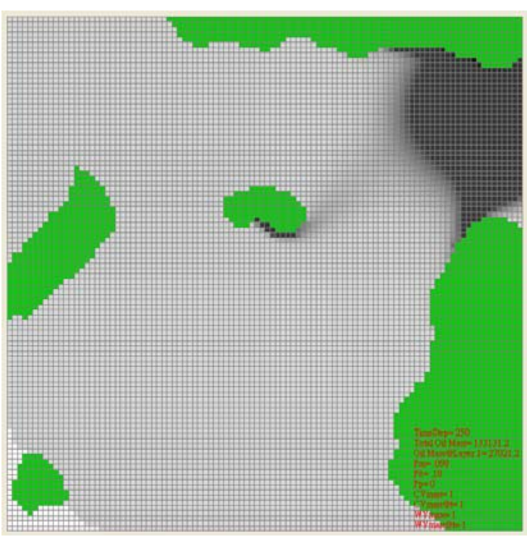
Fig. 12 Case 3 at time step tm=250 at layer 1

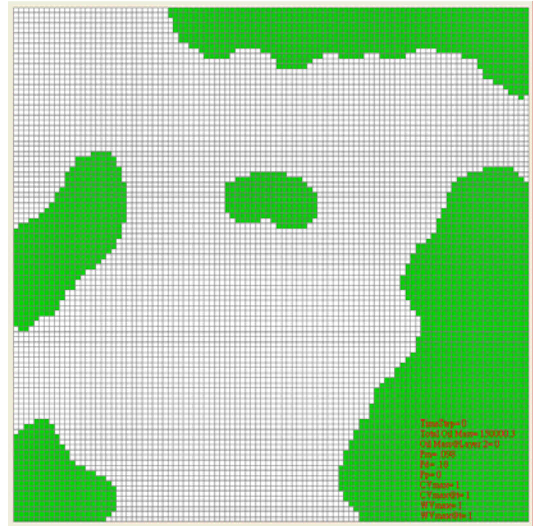
Fig. 13 Case 3 at time step tm=0 at layer 2

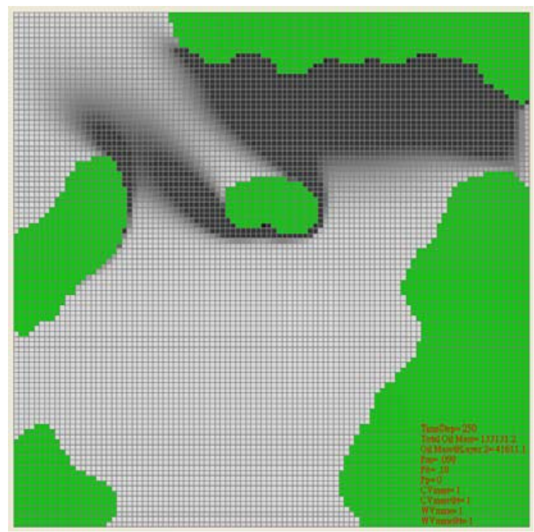
Fig. 14 Case 3 at time step tm=250 at layer 2

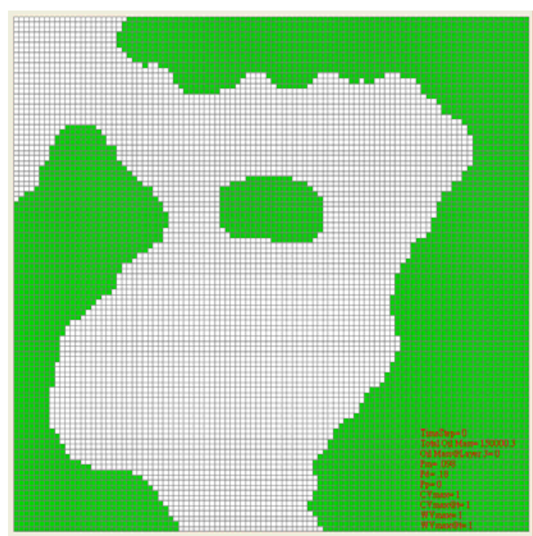
Fig. 15 Case 3 at time step tm=0 at layer 3

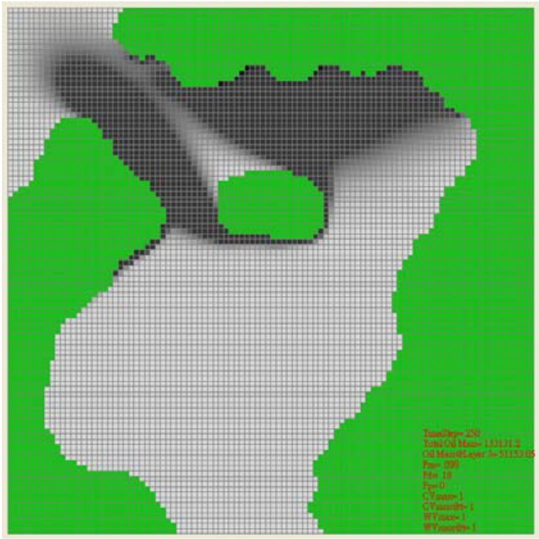

Fig. 16 Case 3 at time step tm=250 at layer 3

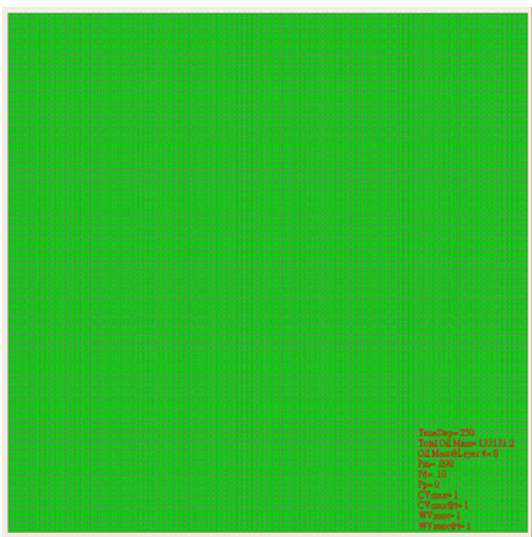

Fig. 17 Case 3 at time step tm=0 and tm=250 at layer 4