International Journal of Environmental Protection and Policy
2022; 10(3): 59-66
http://www.sciencepublishinggroup.com/j/ijepp
doi: 10.11648/j.ijepp.20221003.13
ISSN: 2330-7528 (Print); ISSN: 2330-7536 (Online)

Study on the Key Technology of Deepwater Oil Spill Simulation in the South China Sea

Jianwei Li[1, 2], Wei An[2, *], Yuanshou He[2], Weiwei Jin[2], Shasha Song[2]

[1]Key Laboratory of Marine Environment and Ecology, Ministry of Education of China, Ocean University of China, Qingdao, China
[2]CNOOC Energy Technology & Services Limited, Safety & Environmental Protection Branch, Tianjin, China

Email address:

anwei2@cnooc.com.cn (Wei An)
[*]Corresponding author

To cite this article:

Jianwei Li, Wei An, Yuanshou He, Weiwei Jin, Shasha Song. Study on the Key Technology of Deepwater Oil Spill Simulation in the South China Sea. *International Journal of Environmental Protection and Policy*. Vol. 10, No. 3, 2022, pp. 59-66. doi: 10.11648/j.ijepp.20221003.13

Received: April 21, 2022; **Accepted**: May 31, 2022; **Published**: June 1, 2022

Abstract: With the development of oil and gas fields in deepwater areas, the risk of deepwater oil spill accidents is increasing. In order to improve the capacity of deepwater oil spill contingency response and management in the South China Sea, an user-friendly and robust 3D (three-dimensional) underwater oil spill simulation system is developed by using the MFC (Microsoft Foundation Classes) interface library and the 3D OSG (Open Scene Graph) rendering engine. Many key technologies including submarine topography drawing, sea surface emulation, three-dimensional current display and oil particle simulation are developed and integrated, and the functions including 3D simulations of marine environment and deepwater oil spill prediction are also implemented in the simulation software system. The 3D oil spill simulation system has been applied in the preparation of oil spill response plans (OSRP) for Liwan 3-1 Block, Liwan 43-11 Block, Chevron's Block 42-05 and Baiyun Block in the South China Sea. Preliminary application shows that the system can provide convenient and intuitive visual interactive services for the exploitation of oil and gas resources in the deepwater area of the South China Sea. Meanwhile, the system also specifies underwater trajectories of oil spill in deep waters, the concentration distribution of oil spilled in water, and the time and place the spilled oil reaches the surface, thus providing technical support for on-scene oil spill emergency response and marine environmental impact assessment.

Keywords: Underwater Oil Spill Simulation, 3D Simulation System, Oil Spill Emergency

1. Introduction

Since the Deepwater Horizon oil spill occurred in the Gulf of Mexico in 2010, the countries and companies that exploit deepwater oil and gas resources have attached great importance to the prevention and control of deepwater oil spill. There are also abundant oil and gas resources in deep waters of the South China Sea. However, special regional environment, complex hydrocarbon reservoir characteristics as well as defects of exploration and production (E&P) technologies and engineering equipment bring more challenges to oil and gas development in deep waters. In the face of the increase of accident risks, China is inexperienced with preventing oil spills in deep waters and lacks emergency handling capabilities. Therefore, it is imperative to develop techniques for emergency disposal of oil spills in deep waters. After an oil spill, it is the most important for emergency response operations on the scene to quickly learn when and where the spilled oil rises from the seabed to the surface. Therefore, the establishment of 3D simulation system for oil spills in deep waters can provide important decisions for oil spill emergency response.

Earlier in the 1970s, researches have been made abroad on underwater oil spill simulation. Winiarski and Frick proposed a Lagrange approach to simulate plumes in water bodies [1]. Using two oil spill models – CDOG and DEEPBLOW [2], the whole process of underwater oil spill in deep waters was successfully simulated, and the results are proven well by the experimental data, which provides decision support for oil spill emergency response [3]. Domestic scholars have also carried out researches on underwater oil spill simulation, and the underwater oil spill model is becoming more and more accurate and can be applied to practice [4-7]. However, the visualization of the output data from existing underwater oil spill models is mainly based on 2D visualization [8-11] (e.g. domestic SIMPACT-SOS [12] and foreign OSCAR [13] and OILMAP [14] software), which cannot provide scientific support for the emergency decision-making during oil spill in deep waters in a more direct and visual 3D display mode.

In view of the lack of 3D simulation systems and engineering management systems for oil spill simulation results at home and abroad, an oil spill simulation subsystem and a data management subsystem have been developed based on the established deepwater oil spill model, which realizes visualization of deepwater oil spill simulation results and management of engineering projects and provides technical support for emergency disposal and environmental impact assessment (EIA) of underwater oil spill accidents. They have also been applied in the preparation of emergency response plans (ERP) for the development of deepwater oil and gas fields in the South China Sea.

2. Model of Underwater Oil Spill in Deepwater

As the process of oil spill in deep waters is relatively complicated and hydrates are formed at high pressure and low temperature, the hydrate will decompose and release gas when it rises to low-pressure shallow water. Hydrate formation will reduce the buoyancy of plumes to a great extent. Oil droplets ascend only under the action of their own buoyancy, and their movement is obviously affected by horizontal crossflow, so that the oil droplets with different particle sizes are separated from each other. Larger oil droplets reach the surface first, while smaller ones reach the surface slowly and travel over greater distances under the action of ocean current. In addition, the process of oceanic diffusion will also affect the retention time of oil droplets in water bodies, further increasing the separation of oil droplets. According to above-mentioned oil spill behaviors, the oil spill can be divided into three stages, i.e. jet, plume and convection diffusion; the jet stage and plume stage are buoyant jet plume process, and the convection diffusion stage is convection diffusion process. The oil spill model is as described in Table 1 [16] (the algorithm and formula for determining the synthesis and decomposition of hydrates are derived from Yapa's research results [15], and refer to the research results for specific modeling route and details [5, 7].

Table 1. *Descriptions of the deepwater oil spill model.*

Stage	**Jet**				**Plume**		
Model	**Plume Dynamics Model**						
Simulated Object	**Water**		**Oil**		**Gases**		
Physical and Chemical Process	**Entrainment**	**For hydrates**	**Dissolve**	**Diffusion**	**Dissolve**	**gas-oil separation**	**For hydrates**
Description Method	Mass Conservation Equation: $\frac{dm}{dt}=\rho_a Q_e-\sum_{i=1}^{n}\frac{dm_i}{dt}-\frac{dm_{dif}}{dt}$ Momentum Conservation Equation: $\frac{d(m\vec{V})}{dt}=\rho_a Q_e\vec{V}_a+m\frac{\Delta\rho}{\rho}g\vec{k}-\frac{d(m_{dis+dif}\vec{V})}{dt}-\rho 2bhC_D\left(\lvert\vec{V}\rvert-V_a'\right)^2\frac{\vec{V}}{\lvert\vec{V}\rvert}$						

Stage	**Convection Diffusion**									
Model	**Convection Diffusion Model**									
Simulated Object	**Oil**				**Gases**					
Physical and Chemical Process	**advection**	**Diffusion**	**Floating**	**Dissolve**	**advection**	**Diffusion**	**Floating**	**Dissolve**	**gas-oil separation**	**For hydrates**
Description Method	Convection Diffusion Equation: $\frac{\partial C}{\partial t}+\vec{V}\cdot\nabla C=\nabla\cdot\left(\vec{K}\cdot\nabla C\right)+\sum_{i=1}^{m}S_i$ Lagrange Particle Tracking (LPT) Method: $\frac{d\vec{S}}{dt}=\vec{V}+\vec{V}'+w_b\vec{k}$, $\vec{V}'=\sqrt{\frac{6}{\Delta t}}\left(R_x\sqrt{K_h},R_y\sqrt{K_h},R_z\sqrt{K_z}\right)$									

2.1. Buoyant Jet Plume Process

With regard to this process, consideration should be given to mass conservation process, hydrodynamic process and thermodynamic process of oil, gas, seawater and hydrate, and Lagrange method is usually used to track and describe the location and status of control volumes. In particular, we need to consider the mass conservation of fluid, the mass loss caused by hydrate formation and gas dissolution, the mass loss of hydrate caused by hydrate decomposition and dissolution, the momentum conservation process, the heat conservation process, and the salinity conservation process. At the same time, gas volume change and entrainment are also important factors to be considered.

2.2. Convection Diffusion Process

The motions and interactions of oil, gas and hydrate should be considered in this process, usually using random-walk technique. Oil, gas and hydrate are regarded as aggregates composed of a large number of particles, each containing different substances (oil droplets, bubbles or hydrate particles) and different in size from each other. These particles can move in three-dimensional space, and their features such as mass and volume also change over time.

About the above-mentioned two processes, consideration should be given to hydrate formation and decomposition, oil-gas separation and gas dissolution. The emulsification process and the interaction between oil and sediments in water are also important processes to be considered [17]. Based on researches on jet plume process and convection diffusion process, the underwater oil spill in deep waters is modeled by Lagrange integration method and particle tracking method [18].

3. Development of 3D Simulation System for Oil Spill in Deepwater

3.1. R&D Requirements

With a visual interface, the whole process of underwater oil spill will be displayed in real time. A 3D visualization system with convenient operation, stable operation and friendly interface is established to realize real-time display of simulation results and rapid information release. At the same time, the system can manage project information, oil spill information, simulation results and other data, providing technical support for oil spill response exercises, contingency planning, and oil spill decision making.

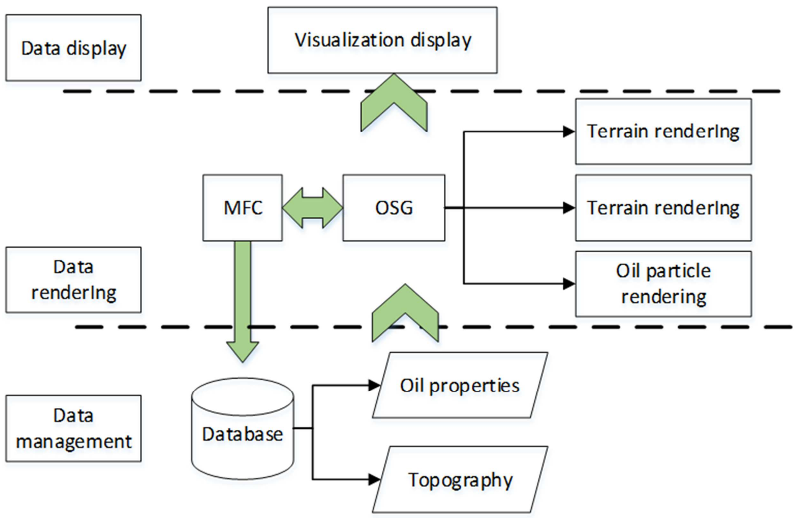

Figure 1. *The 3D visualized simulation system frame.*

3.2. Overall Architecture

Figure 1 shows a frame diagram of the 3D visualized simulation system, from which it can be seen that the system is divided into visual interface display, 3D data rendering and underlying database management. Figure 2 shows a roadmap to develop the visualization technology for the 3D simulation system for oil spill in deep waters. Next, we will introduce the system development process by "bottom-up" approach.

(1) In terms of underlying database management, ACCESS data are mainly used to design database structures such as basic project information, geographic background information, oil spill location information, and model calculation parameters, so as to realize efficient management of the data generated by the oil spill model.

(2) In terms of 3D data rendering, MFC (Microsoft Foundation Classes) interface library and OSG (Open Scene Graph) 3D rendering engine are mainly used to complete the visual rendering of data on oil spills in deep waters, and simultaneous multi-threading technique is used to isolate interface operations from data rendering, thus creating a 3D environment platform with convenient operation and dynamic display. Through OSG 3D rendering engine-based researches on GPU (Graphic Processing Unit) parallel computing technique, 3D scene interaction technique, particle system and Delaunay fast terrain modeling technique, the 3D dynamic simulation of seabed terrain, sea surface, current and oil spill particles is realized.

(3) Visual interface display is mainly realized by MFC interface library. The MFC interface library contains an application framework based on view architecture. The program data are maintained by document objects and provided to users through view objects, while OSG provides visual interfaces related to scene management and graphics rendering and operator interfaces (O/I) for keyboard, mouse and other devices. Therefore, 3D visual scenes with user-friendly interactive interfaces can be built by integrating the OSG visual graphics library based on MFC user interaction framework.

3.3. Key Visualization Techniques for Simulation System Development

3D visualization is a key technology for oil spill simulation system. In this paper, the realization of such techniques as real-time seabed terrain rendering, sea surface simulation, 3D current display, and oil spill particle simulation is mainly discussed.

3.3.1. Real-Time Seabed Terrain Rendering Technique

Topographically, seabed is generally undulating and uneven. Therefore, the terrain simulation data are different from regular row, column and grid data and they exhibit irregularity. Delaunay is applied to rapidly complete the terrain modeling based on irregular grid data, and by using the vertex array index binding technique for OSG 3D rendering engine, the calculation of vertex data is reduced in the process of rendering triangular patches, thus realizing efficient and fast rendering of large-scale ocean topographic data.

Light environment is an important factor that must be considered in the 3D rendering of complex ocean terrain. OpenGL (Open Graphics Library) mainly realizes lighting effects through face normals and vertex normals. Only the light reflected from a single plane element is considered for the face normal. Due to the undulating terrain, there is a large difference in reflection of light between adjacent plane elements. In order to make the overall lighting effects smoother, the contribution values of all plane elements sharing this vertex should be considered for the vertex normal.

Based on the lighting effects using vertex normals and the highlighted terrain level difference, the system uses GPU point-based rendering and GLSL (Open GL Shading Language) high-level shading language to achieve differentiated coloring of terrain at different heights. The seabed terrain effect is shown in Figure 2.

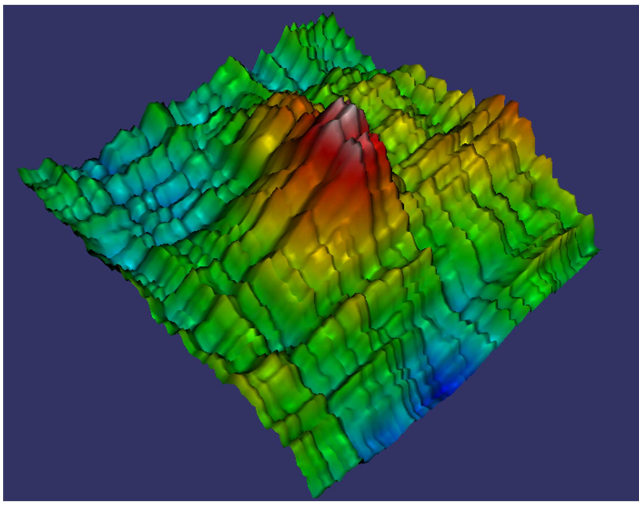

Figure 2. *Seabed terrain results show.*

3.3.2. Sea Surface Simulation Technique

Compared with the 3D visualization of other ocean environments, the simulation of sea surfaces is more complicated, because it is necessary to consider not only irregular wave motion but also light and its reflectance factor. The system uses texture-based sea surface simulation to realize sea surface rendering quickly and efficiently.

In reality, waves on the ocean are rising and falling, and show ripple effects under the influence of sea breeze. Bump mapping and normal mapping are mainly used. The bump mapping technique mainly realizes the simulated effect of undulatory sea surface, while the normal mapping technique relies on the dynamic change of texture sample coordinates to give the vision of the sea surface model surface in motion. In addition, GPU is used to change texture coordinates to improve rendering efficiency and realize sea surface simulation of high-frequency ripples with different jump details.

3.3.3. Current Display Technique

Current display is to better simulate the ocean environment and more clearly observe the impact of ocean currents on oil spills. Based on the current vector arrow drawing method, the dynamic display of currents in three-dimensional space is realized. Current 3D simulation is mainly based on OSG geometry rendering, which is realized by applying scene tree, node access and callback mechanism. It can add multiple graph primitives to a geometry object and improve rendering efficiency through VBO (Vertex Buffer Object). At the same time, an arrow drawing algorithm is applied to control the magnitude and direction of current. After obtaining the four points at which to draw an arrow, the drawing primitives are set by Primitive Set. Finally, leaf nodes are added to plot and render, and the dynamic display of data is updated through node callback. The size and direction of the arrow drawn are determined according to the longitude and latitude vector values of current at grid point. The display effect of 3D flow field is shown in Figure 3.

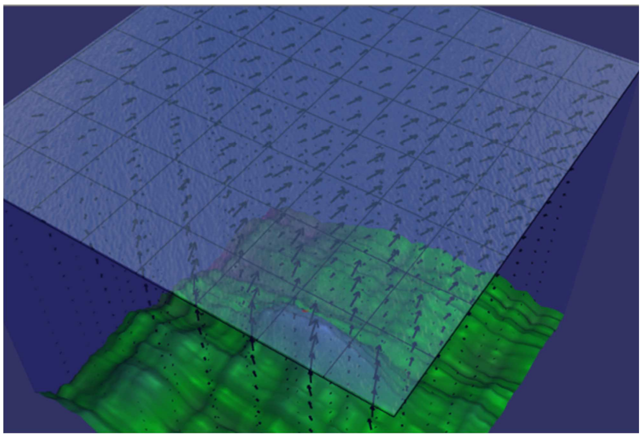

Figure 3. *Display of 3D flow field.*

3.3.4. Oil Spill Particle Simulation Technique

Oil spill particle system is the core module of oil spill visualization, and the particle system adopted is the most successful generation algorithm for irregular fuzzy objects so far. The particle system describes the comprehensive state of individual particles at a certain point by means of multi-dimensional attributes such as 3D coordinates, time, speed, direction, radius, etc. Through particle swarm optimization, a wide variety of particles that are changing states all the time are simulated in three dimensions, which has the advantage of simulating complex objects through simple voxel units.

In view of complex and changeable oil spreads in the marine environment, it is of great significance for the particle system to simulate and dynamically plot the state of oil spill particles. However, due to the large amount of data on oil spill particles, it requires extremely high CPU processing capacity and rendering speed. The simulation by particle system, based on GPU's parallel computing capacity, reduces the dependence of rendering on CPU (Central Processing Unit), maximizes the rendering efficiency, and mainly uses VBO. The VBO technique will perform write operations only when data are initialized or updated, which greatly reduces the data copies between CPU and GPU. VBO also supports primitive updates and can improve rendering efficiency by using VA (Vertex Array) and DL (Display List) data. The types of particles can be distinguished by different color settings, mainly including oil particles, bubbles and hydrates, etc. with different particle sizes. In the display process, yellow represents hydrate, red represents natural gas, green represents large oil droplet (more than 1,000μm in size), blue represents medium oil droplet (ranging in size from 500μm to 1,000μm), and black represents small oil droplet (less than 500μm in size), as follows. The effect of oil spill particles is shown in Figure 4.

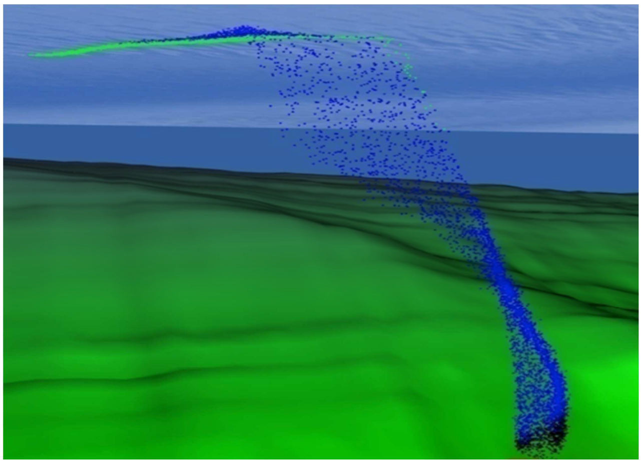

Figure 4. *Emulation of oil spill particles.*

3.4. Realization of Simulation System Function

3.4.1. Dynamic Prediction of Oil Spills in Deep Waters

The simulation system can call deepwater oil spill prediction model and 3D hydrodynamic prediction data to realize trajectory prediction of underwater oil spill in deep waters. Users can quickly input accident parameters and model parameters to complete forecast and analog computation, and quickly display the drifting trajectories of underwater oil spill in a 3D visualization system so as to determine when and where the underwater oil rises and dynamic information. In the calculation process, the fate of the underwater oil is also calculated in real time, including total amount of oil spilled, amount of oil rising to the surface, and amount of oil in water.

3.4.2. 3D Simulation and Control

3D simulation and control is the kernel of the system, controlling the whole interface display process. Scene control is realized through man-machine interaction (HMI). The system provides menu bar, toolbar, dialog box, floating column and other interactive interfaces to facilitate action control and provide necessary feedback. The man-machine interaction is optimized through extended functions such as zoom in, zoom out, rotate, pan and sight extension/retraction. Finally, the system realizes the 3D simulation of seabed terrain, sea surface and oil spill and the synchronous display of oceanic 3D flow fields.

In order to enhance the display effect of the 3D visualization system, the system can load and display common offshore oil facilities, including platforms, pipelines and ship models, etc., and provide 3D annotation in 3D ocean scenes.

3.4.3. Output

The system’s simulation results are mainly output through images, videos, intelligence reports and other various forms. Based on the field needs, the system can output and store the entire simulation process in an image or video format, and can also quickly generate accident reports and forecast reports, thus providing technical support for oil spill response commanders.

3.4.4. Data Management

Large quantities of data such as model parameters, historical project information and simulation results will be generated in the process of numerical simulation of underwater oil spill, so a database management module is developed for effective data management. The database mainly includes historical project information, new project parameter setting, details view and other functions. Historical project management is used to show history, conditional filter, selective deletion and other functions, to provide unified management of historical events in the system, and to increase the availability of the system. Setting of model parameters is a prerequisite for launching the deepwater oil spill model. After the setting is completed, data streams are passed to the model as the initial operation condition, and the model parameters of historical projects are viewed in real time. Details view provides functions such as input, modification, deletion and query of parameters for numerical simulation of oil spills in deep waters through a friendly human-machine interface to manage and invoke data.

3.5. System Service Model

This system is featured by full functionality, stability, high control response speed, and support to 3D perspective modes such as mouse dragging, keyboard operation, button operation, etc. The communication interface for calculation models is convenient and easy to use, and has high communication efficiency. The system adopts modular design, including offshore hydrodynamic data, oil spill simulation and 3D visualization as independent function modules, which can provide targeted technical services and customize solutions for users. Please see Figure 5 for the system interface.

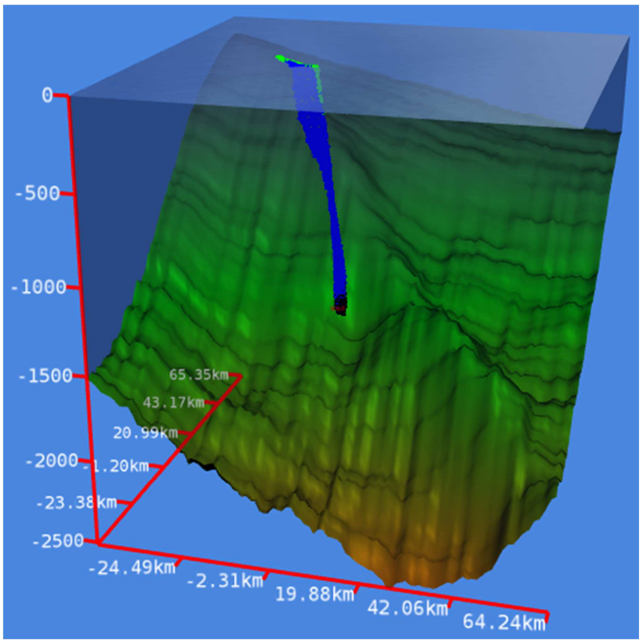

Figure 5. *Main interface of the system.*

4. Case Application

The 3D oil spill simulation system has been applied in the preparation of oil spill response plans (OSRP) for Liwan 3-1 Block, Liwan 43-11 Block, Chevron's Block 42-05 and Baiyun Block in the South China Sea. In order to explain the effectiveness and reliability of the system, Liwan 3-1 Block (115°25′E, 19°54′N) was selected in this case, assuming that an oil spill occurs at depth of 1,378m and lasting for 24h; the simulation time is 48h (November 7 - 9, 2012); the density and temperature of crude oil are 811 kg/m^3 and 90°C respectively, containing methane; the wellhead radius is 0.1m, the jet velocity at wellhead is 2 m/s, and the amount of oil spilled is 1,000 m^3. Oil spill simulation parameters are detailed in Table 2.

In the simulation process, data on current, temperature, salinity and seawater density of the South China Sea are derived from the 3D tidal current prediction system of the First Institute of Oceanography of the State Oceanic Administration [19]. The water depth in most parts of the South China Sea ranges from 1,000m to 2,000m. At most continental shelves in the north, there are irregular semi-diurnal currents, while in deep waters, there are mainly irregular diurnal currents. During the simulation, 10,000 Lagrangian particles are set in the oil spill model to simulate spilled oil trajectories. The particle size distribution is skewed in the range of 6-5,000 μm, with an average particle size of 250 μm and a standard deviation of 75 μm.

Table 2. *Oil spill simulation parameters.*

Project information	Parameter value for
Oil Spill Point	115°25′E, 19°55′N
Simulation Time	November 7 - 9, 2012
Water Depth/m	1442
Oil Spill Duration/h	24
Simulation Duration/h	48
Nozzle Diameter/m	0.1
Crude Oil Density/kg/m^3	811
Oil Spill Volume/m^3	1000

According to the results of numerical simulation of the system, the natural gas released at low temperature and high pressure after 1.5min oil spill rises to 1,362.7m where hydrates are formed (Figure 6a), and rises to 756.9m after 1.3h oil spill where hydrates decompose into natural gas (Figure 6b). Large oil droplets ascend quickly and reach the surface after 3.5h oil spill. Due to a certain vertical distribution structure of horizontal currents, the oil particles at the leak point move east by north, then shift toward the northwest at a depth of about 840m. Finally, the large oil droplets emerge from the surface, 4.9km northwest of the leak point (Figure 7a). After 4.5h oil spill, medium oil droplets reach the surface, and the location where they emerge from the surface is 6.3km northwest of the leak point, which is farther north than the location where the large oil droplets emerge (Figure 7b).

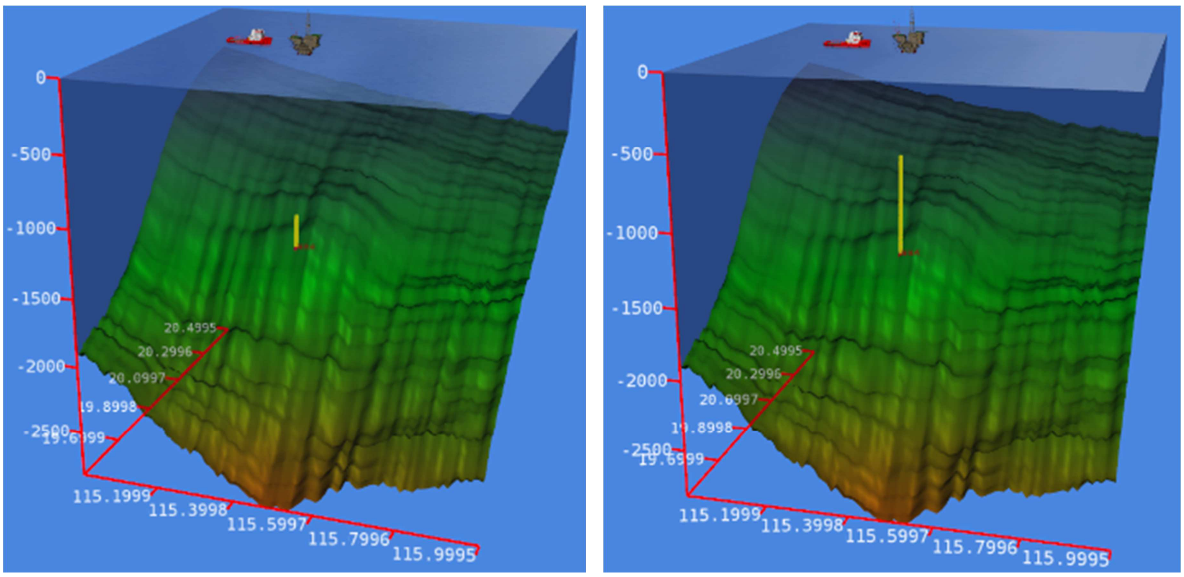

Figure 6. *Hydrate change process (a: formation; b: decomposition).*

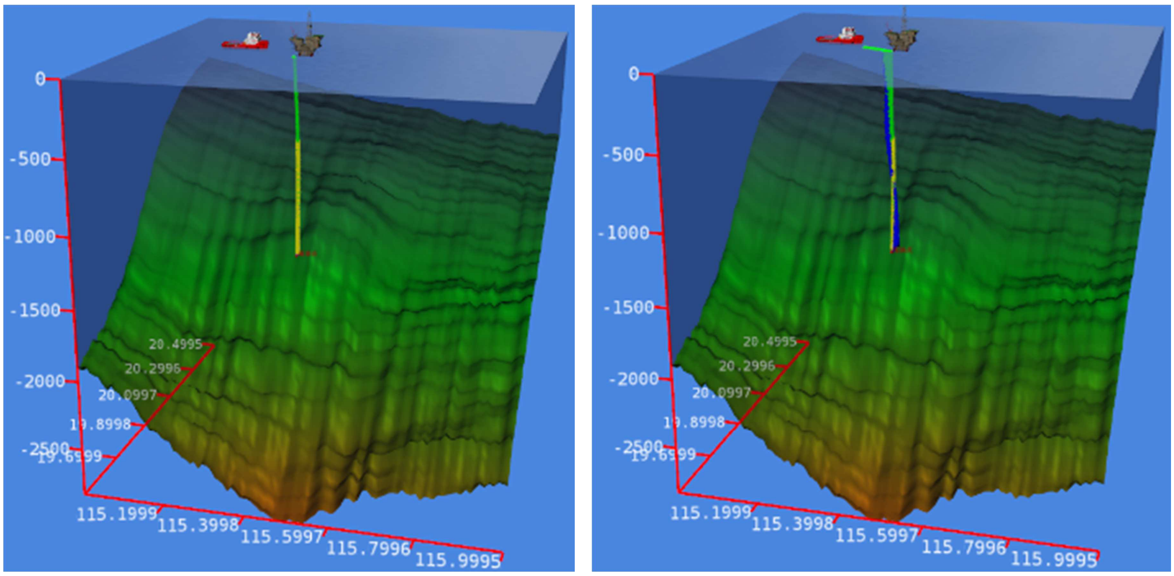

Figure 7. *Oil droplets reaching sea surface (a: big; b: middle).*

After 24h oil spill, the oil particles move to different extents in the east, west and north under the action of their own buoyancy and ocean current. The oil contamination is generally located on the north side of the leak point. Meanwhile, the oil particles reaching the surface continue to diffuse northeastward under the action of ocean currents (regardless of wind fields), with the horizontal maximum diffusion distance of 15.8km (Figure 8a). After 48h oil spill, the oil particles at the leak point move eastward, and the oil particles in shallow water and on the surface move northwest, with the horizontal maximum diffusion distance of 25.7km. At the same time, some of medium oil droplets and all of small oil droplets are distributed underwater, and small oil droplets are almost suspended and still in deep waters beyond 1,000m (Figure 8b).

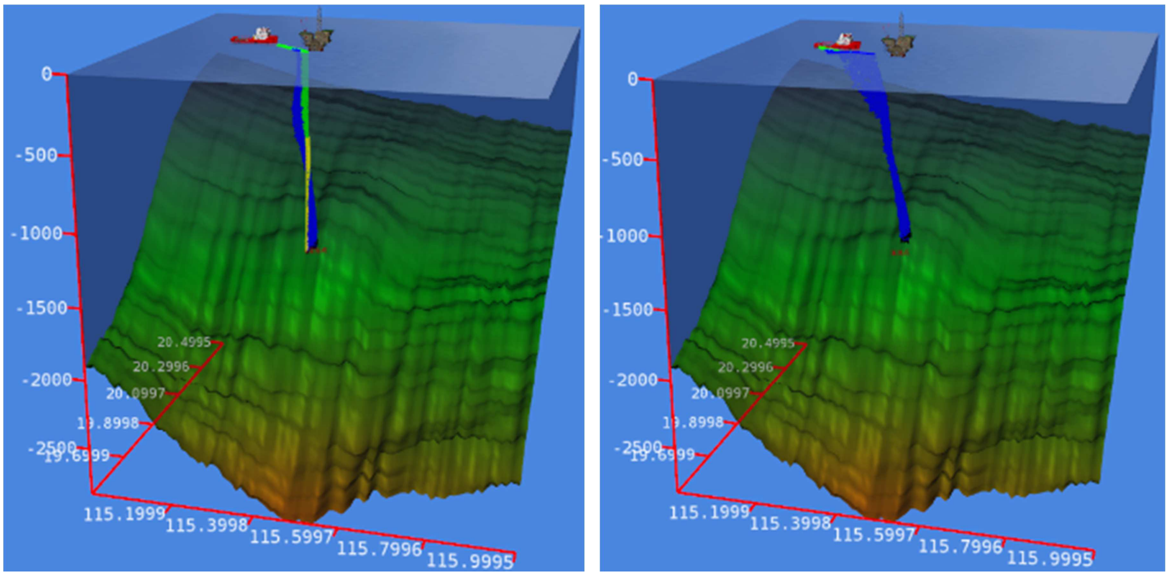

Figure 8. *Oil droplets transport and dispersion (a: 24h ; b: 48h).*

5. Conclusion

In order to improve the ability in responding to oil spills in deep waters of the South China Sea, some researches have been made on key techniques such as seabed terrain rendering, sea surface simulation, 3D current display and oil particle simulation, based on MFC interface library and OSG 3D rendering engine. A 3D visualization system with convenient operation, stable operation and friendly interface has also been developed. The system mainly serves underwater oil spills such as blowout, subsea pipeline rupture and shipwreck, and specifies underwater trajectories of oil spill in deep waters, the concentration distribution of oil spilled in water, and the time and place the spilled oil reaches the surface, thus providing technical support for on-scene oil spill emergency response and marine environmental impact assessment.

In the future, we will continue to improve the function of the 3D underwater oil spill simulation system, such as underwater dispersants simulation, natural gas leakage simulation, and CO_2 leakage simulation.

Acknowledgements

This research is supported by the National Natural Science Foundation of China (41976176); the National Key R&D Program of China (2016YFC1402306, 2019YFC1408404). We also acknowledge the constructive and valuable comments and suggestions of the reviewer and the editor.

References

[1] Winiarski LD, Frick WE. Cooling tower plume model [R]. Report EPA-600/3-76-100, U.S. Envir. Protection Agency, Corvallis, Oreg, 1976.

[2] Johansen Ø. Development and verification of deep-water blowout models [J]. Mar Pollut Bull, 2003, 47, 360-368.

[3] Yapa P D, Dissanayake A L. Bubble plume modelling with new functional relationships [J]. J Hydraul Res, 2012, 50, 646-648.

[4] LIAO Guoxiang, YANG Jianqiang and GAO Zhenhui. Preliminary Numerical Simulation of Oil Spill Transport and Diffusion in Deep Sea Environment [J]. Marine Science Bulletin, 2011, 30 (6): 707-712.

[5] CHEN Haibo, AN Wei, YANG Yong et al. Research on Numerical Simulation of Underwater Oil Spill [J]. Ocean Engineering, 2015, 33 (2): 66-76.

[6] Chen Haibo, An Wei, You Yunxiang, et al. Modeling underwater transport of oil spilled from deepwater area in the South China Sea [J]. Chinese Journal of Oceanology and Limnology. 2015, 33 (5): 1-19.

[7] Chen Haibo, An Wei, You Yunxiang, et al. Numerical study of underwater fate of oil spilled from deepwater blowout [J]. Ocean Engineering. 2015, 110: 227-243.

[8] LI Yan, LIU Qinzheng and ZHANG Cunzhi. Introduction to the Operational Forecast System for Offshore Oil Spill Emergency Response [J]. Marine Forecasts, 2010, 27 (6): 65-71.

[9] YU Feng. Real-time Visualization Simulation of Offshore Oil Spill Based on Physical Model [J]. Journal of System Simulation, 2008, 20: 313-315.

[10] ZHUANG Xueqiang, CHEN Jian and SUN Qian. Numerical Simulation of Oil Spills at Sea and Its Visualization Technique [J]. Navigation of China, 2007 (1): 97-100.

[11] MOU Lin et al. Study on Forecast and Early Warning System for Emergency Response of Oil Spills in Bohai Sea II. Visualization and Operational Application of the System [J]. Marine Science Bulletin, 2011, 6 (36): 234-238.

[12] LIAO Guoxiang, YANG Jianqiang and GAO Zhenhui. Visual Numerical Simulation System for Submarine Oil Spill Transport and Diffusion [J]. Journal of Wuhan University of Technology (Transportation Science & Engineering), 2011, 35 (4): 748-751.

[13] Reed, M., P. S. Daling, O. G. Brakstad, et al. OSCAR2000: A Multi-Component 3-Dimensional Oil-Spill Contingency and Response Model [J]. Proceedings to the 2000 Arctic and Marine Oilspill Program Technical Seminar, Vancouver, Canada, June 14-16 2000.

[14] Spaulding, M. L., Mendelsohn, et al. Draft Technical Reports for Deepwater Horizon Water Column Injury Assessment: Application of OILMAP DEEP to the Deepwater Horizon Blowout [R]. Prepared for National Oceanic and Atmospheric Administration (NOAA) by RPS ASA, South Kingstown, RI, U.S.A, 2015.

[15] Yapa P D, Dasanayaka L K, Bandara U C, et al. A model to simulate the transport and fate of gas and hydrates released in deepwater [J]. Journal of Hydraulic Research. 2010, 48 (5), 559-572.

[16] AN Wei, ZHAO Yupeng, LI Jianwei et al. Development and Application of 3D Visual Simulation System for Underwater Oil Spill in Deep Waters of the South China Sea [J]. Ocean Development and Management, 2016, 3: 34-38.

[17] Chen F H, Yapa P D. Tree-dimensional visualization of multi-phase (oil/gas/hydrate) plumes [J]. Environmental Modeling & Software, 2004 (9): 751~760.

[18] Reed M, Morten H E, Ben H, et al. Numerical model for estimation of pipeline oil spill volumes [J]. Environmental Modelling & Software, 2006, 21 (2): 178-189.

[19] Wang Y G, Wei Z X, Lian Zh, et al. Development of an ocean current forecast system for the South China Sea [J]. Aquatic Procedia, 2015, 3, 157 – 164.