Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No.

Modelling dispersion processes of radioactive materials in a maritime environment for emergency response to maritime transport accidents involving radioactive material packages

Mitsufumi ASAMI
National Maritime Research Institute

Hideyuki OKA
National Maritime Research Institute

Abstract

A numerical simulation model that consists of an ocean flow model, called MASs-CONsistent flow simulation model (MASCON), and a dispersion model has been developed to describe the behavior of dispersion processes of radioactive materials in a shallow water region. The use of the model enables several assessment of radioactive materials concentration distributions in the ocean due to release from the sunken package. Further, the dispersion calculation is able to perform in a short time which responds to emergency action for maritime transport accidents involving radioactive materials. Radioactive materials in the ocean are modeled in three phases; a dissolved phase in seawater, a suspended matter phase, and active bottom sediment phase. The adsorption and desorption processes between the dissolved, suspended matter, and active bottom sediment phase are solved by a kinetic approach to describe the transfers of radioactive materials between the liquid and solid phases. The simulation model was applied to simulate the dispersion of ^{137}Cs actually released into the environment by the Fukushima Daiichi Nuclear Power Plant accident in March 2011. A simulated result indicates that the modelling of contribution from all three phases to the seabed sediment is important to reproduce the vertical distribution of radioactive materials in the seabed sediment.

Introduction

National Maritime Research Institute has developed a supporting system for emergency response of competent authority to maritime transport accidents involving radioactive materials. The supporting system for emergency response has functions of radiation shielding calculation, atmospheric or ocean dispersion simulation, and radiological impact evaluation to grasp potential hazard of radiation. Recently, measurements of radioactive materials on the seafloor in shallow water region around Fukushima Daiichi Nuclear Power Plant (1F NPP) revealed that radioactive materials are distributed not only in the surface of the seabed sediment but in the deeper region (NRA, 2015a, 2015b). The evaluation of temporal change in concentration of radioactive materials in seabed sediment is important to supply valuable information for the effects on fishery resources. To enhance functions of the supporting system for the effects on fishery, feasibility of improvement of the current ocean dispersion model is discussed in this article.

Numerical Models

1. Ocean Circulation Data

A data set of Japan Coastal Ocean Predictability Experiment 2 (JCOPE2) is used for simulating radioactive materials behavior in the sea of ^{137}Cs released from the 1F NPP reactors off Fukushima. The JCOPE2 data set is derived from an ocean forecast system where a three-dimensional variational assimilation method is incorporated into a numerical model based on the Princeton Ocean Model with a generalized sigma coordinate (Kagimoto et al., 2008). Horizontal resolution for the ocean used in this article is 1/36 degree.

2. Seafloor Topography

Seafloor topography which influences ocean circulation is based on a data set of JODC-Expert Grid data for Geography (J-EGG500) from the Japan Oceanographic Data Center (JODC) of the Hydrographic and Oceanographic Department, Japan Coast Guard (JHOD): a huge amount of the depth-sounding survey data around Japan, which were taken by JHOD and also various ocean research institutes, have been integrated and gridded by 500m intervals to be used for general purposes (JODC, 2016).

3. Three dimensional current field

In this article, MASs-CONsistent flow simulation model (MASCON) was used to simulate three-dimensional current field, which was designed to allow efficient calculation of flow field which is relatively large space-scale such as ocean circulation (Dickerson M. H., 1978). Scheme of deriving current field by MASCON is shown in Figure 1. MASCON is based on the principle of mass conservation in which divergence is eliminated in a flow field. Given a limited number of observations or a coarsely modelled flow field over complex terrain, the flow field is physically interpolated in such a way that mass conservation is satisfied. Mathematically, the problem is to minimize the functional (Sasaki Y., 1958, 1970; Sherman C., 1978).

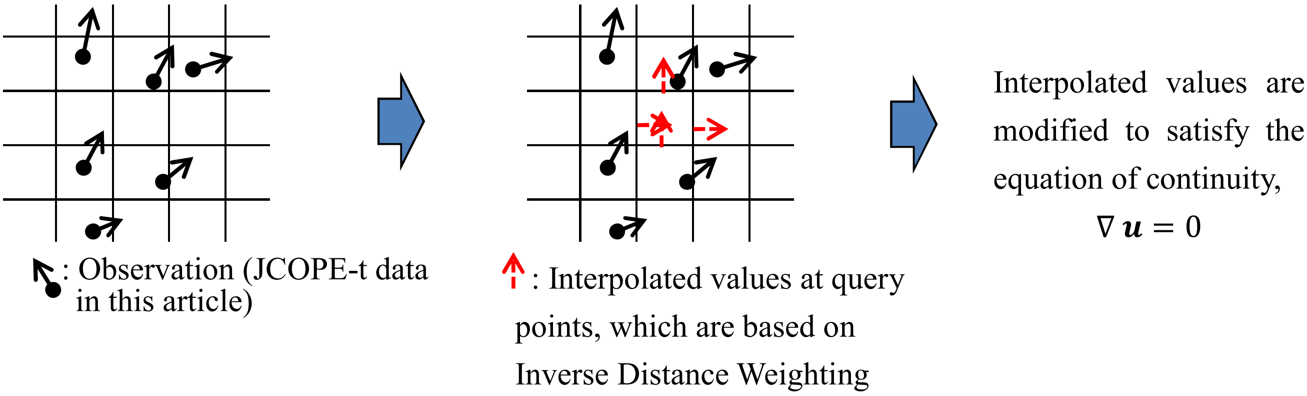
$$\begin{aligned} E(u,v,w,\lambda) = \int_V \Bigg[& \beta_1^2(u-u^0)^2 + \beta_1^2(v-v^0)^2 + \beta_2^2(w-w^0)^2 \\ & + \lambda\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)\Bigg] dxdydz \end{aligned} \tag{1}$$

where x, y are the horizontal coordinates; z is the vertical coordinate; $u^0, v^0,$ and w^0 are the initial observed velocity components; $u, v,$ and w are the corrected velocity components; λ is the Lagrange multiplier; and β_1 and β_2 are Gauss precision moduli, which are the current vector-partitioning factors in the horizontal and vertical directions. The integral domain of the model is V. The corresponding Euler-Lagrange equations can be derived (Sherman, 1978). The resulting equation for λ is a Poisson equation:

$$\frac{\partial^2\lambda}{\partial x^2} + \frac{\partial^2\lambda}{\partial y^2} + \frac{\partial^2\lambda}{\partial z^2} = -2\left(\frac{\partial u^0}{\partial x} + \frac{\partial v^0}{\partial y} + \frac{\partial w^0}{\partial z}\right) \tag{2}$$

The λ value in Eq. (2) can be solved numerically by setting the boundary conditions on all facets of the computation domain. The u, v, w current vector components then can be computed from the Euler-Lagrange equations using the λ value solved from Eq. (2). The iterative convergence will be the high-resolution diagnostic solution for u, v, w for given boundary and coarse initial conditions (observations). At the lateral and top boundaries, u, v, w is set equal to zero to allow flow through in the flow adjustment. At the bottom of the domain no-flow through conditions can be satisfied by having the normal derivative vanish, that is, $\partial\lambda/\partial n = 0,$ where n is the normal to an impermeable surface. A detailed description on the mass-consistent flow field model is referred to in Sherman 1978 and other literatures reviewed in the introduction section. The deficiency of a mass-consistent model is that it is unable to simulate the vortices or wakes in the lee of steep topography because the momentum conservation is not included.

In this article, JCOPE-t data was used as coarse initial conditions in MASCON. The horizontal resolution was 1500 m in both zonal and meridional directions with 300 meshes in the zonal direction and 400 in the meridional direction. The vertical resolution of the Cartesian coordinate system was 100 layers. The ocean floor was set at 500 m depth to reduce the computer resources needed for the simulation. The actual ocean depth reaches more than 1 km in this region.



↖: Observation (JCOPE-t data in this article)

↑: Interpolated values at query points, which are based on Inverse Distance Weighting

Interpolated values are modified to satisfy the equation of continuity,

$$\nabla \boldsymbol{u} = 0$$

Figure 1 Mass-consistent flow simulation model by using ocean circulation data

4. Modeling the transport of suspended sediments

Radioactive materials are fixed to suspended particles and the seabed sediment. Radioactive materials in the dissolved phase and suspended particles are transported by advection and diffusion process. Suspended particles may be deposited on the seabed, and depending on the magnitude of the currents, the seabed sediment may be eroded. This implies a transfer of radioactive materials from the seabed sediment to the suspended particle phase. At the same time, desorption of radioactive materials from the seabed and suspended particles occurs. In this model, two grain size fractions are considered in the seabed sediment. Only the small particles can be re-suspended and incorporated into the water column as suspended matter. To evaluate the accumulation of radioactive materials in the seabed sediment, a sedimentation model was developed and applied to the South Tohoku offshore region.

5. Sediment radioactive material model

Depth of the active bottom sediment phase has assumed to be the accessible length of radioactive materials, which described in calculation condition. Conventionally, concentration of radioactive materials in the active bottom sediment phase has been modelled and calculated as the average of the depth of the sediment (Periañez R., 2005). In this article, the sediment radioactive material model was used to simulate the vertical radioactive materials distribution in the seabed and sedimentation or suspension at the bottom boundary. This model was based on the vertical one-dimensional transport equations for adsorption or deposition of radioactive materials in the sediment (Kutsukake H. et al., 2013); Radioactive materials diffuse vertically in the seabed sediment through pore water. Contribution of suspended matter was modelled as the advection term of permeable flow. Lateral transport into the sediment was negligible. Interaction between the bottom current and topological change of the sediment surface was ignored, and the ideal sediment assumption was used. A schematic view of the interaction processes between three phases proposed in this article is shown in Figure 2.

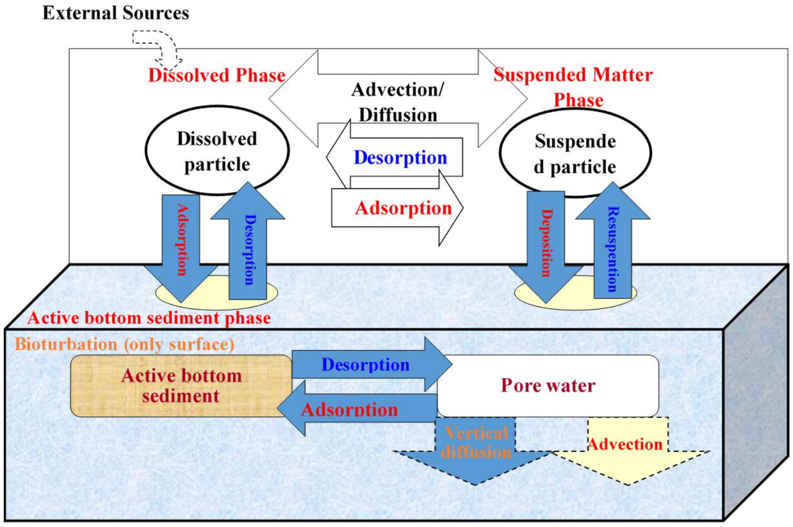


Figure 2 Schematic view of the interaction processes between three phases proposed in this article

Results and Discussion

Computed distribution of ^{137}Cs in sediments

To evaluate the reproduction performance of the sediment radioactive material model, simulated ^{137}Cs in the sediment was compared with observations (Figure 3) near the 1FNPP. This figure is after two years released into the ocean through direct release and leaking of the heavily contaminated coolant water. Sediment sampling data was used from the Nuclear Regulation Authority, which were published in units Bq kg^{-1}-dry. Sediment sampling data was selected in terms of distinguishing vertical distribution of ^{137}Cs in seabed sediment; K1 for the case of the highest concentration at the seabed sediment surface, K3 for the case of deep infiltration in the seabed sediment, and A1N for the case of having two maximum concentration in the different depth in the seabed sediment, respectively. By using the model proposed in this article, spatial variations of the sediment ^{137}Cs were comparable with the observations. On the other hand, conventional model (Periañez R., 2005) or radioactive materials sediment model without consideration of each interaction process between three phases (Kutsukake H. et al., 2013) does not reproduced the maximum value of ^{137}Cs in observations. Therefore, the modelling of contribution from all three phases to the seabed sediment is important to reproduce the vertical distribution of radioactive materials in the seabed sediment.

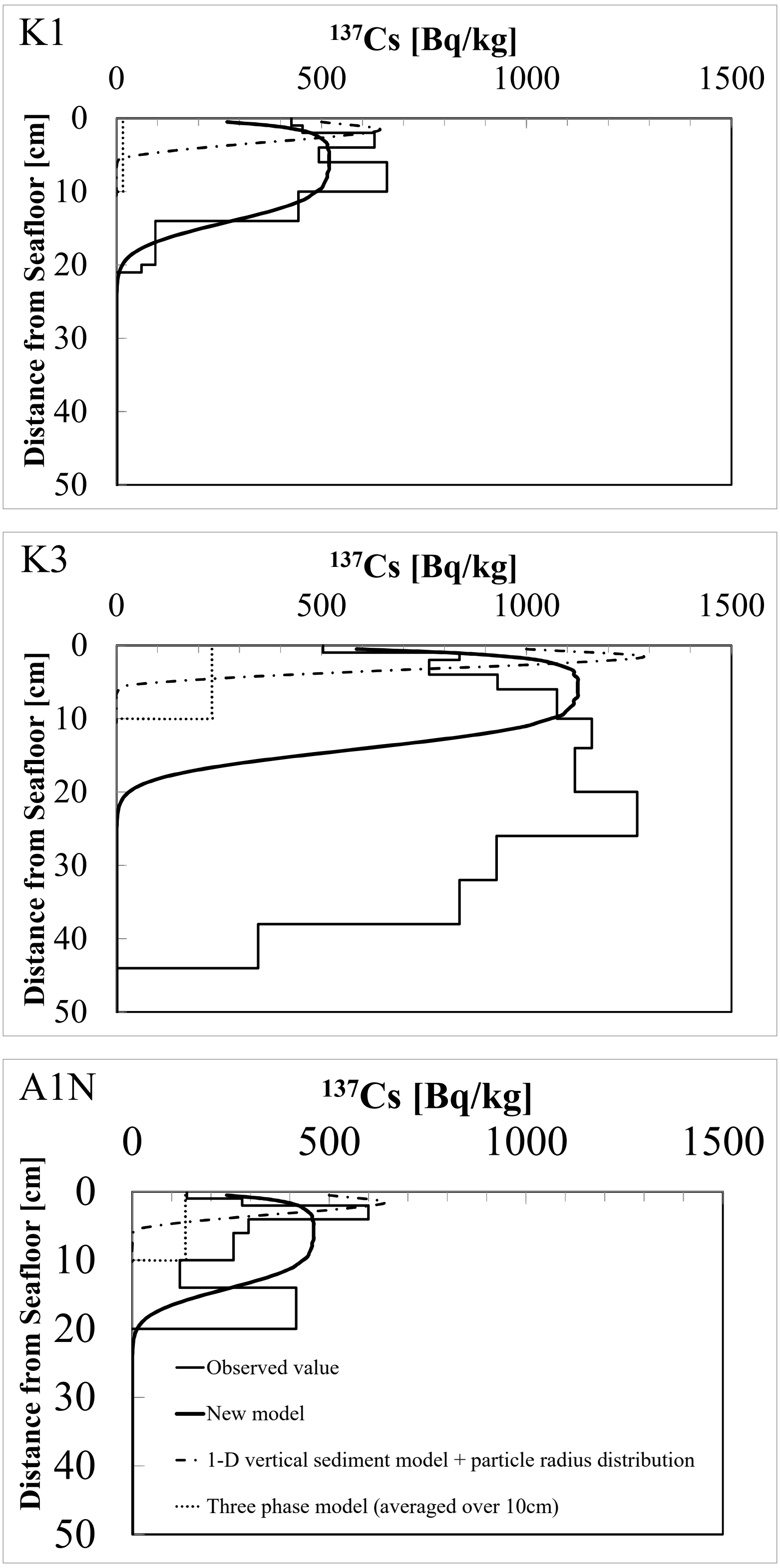


Figure 3 ^{137}Cs concentration distribution in seabed sediment
(Observed value was originated from Reference (NRA, 2015a, 2015b).)

Conclusions

Supporting system for emergency response to maritime transport accidents involving radioactive materials was developed aiming support of accident response of Ministry of Land, Infrastructure and

Transport, Japan, in case of the accident during maritime transport radioactive materials. The simulation model was applied to simulate the dispersion of ^{137}Cs actually released into the environment by the Fukushima Daiichi Nuclear Power Plant accident. A simulated result indicates that the modelling of contribution from all three phases to the seabed sediment is important to reproduce the vertical distribution of radioactive materials in the seabed sediment. Improved ocean dispersion model would be useful for support not only for emergency response during maritime transport accident involving radioactive materials but also for supply of valuable information for the effects on fishery resources.

Acknowledgments

This study was conducted under a contract research "Development of accident assessment system for maritime transport of radioactive material" with Ministry of Land, Infrastructure and Transport, Japan.

References

Dickerson M. H.: MASCON - A mass consistent atmospheric flux model for regions with complex terrain, J. Appl. Meteor., 17, 241-253, 1978.

JODC (Japan Oceanographic Data Center): JODC-Expert Grid data for Geography (J-EGG500), 500m gridded bathymetric data set of Japan. http://www.jodc.go.jp/data_set/jodc/jegg_intro.html (last access: June 2016).

Kagimoto, T., Y. Miyazawa, X. Guo, and H. Kawajiri: High resolution Kuroshio forecast system - Description and its applications-, in High Resolution Numerical Modeling of the Atmosphere and Ocean, W. Ohfuchi and K. Hamilton (eds), Springer, New York, 209-234, 2008.

Kutsukake H., Takeuchi K., and Nakata K.: Analysis of ^{137}Cs sedimentation in ocean bottom from the Fukushima Dai-ichi Nuclear Power Plant (Analysis of ^{137}Cs in ocean sediment), J. Adv. Marine Sci. and Technol. Soc. 19(2), 13-25, 2013.

NRA (Nuclear Regulation Authority): Readings of marine soil monitoring in sea area, 2015a.

NRA (Nuclear Regulation Authority): Change of the radioactivity concentration of the seawater in sea area close to Fukushima Daiichi NPS/coastal sea area, August, 2015b.

Periañez R.: Modelling the Dispersion of Radionuclides in the Marine Environment, Springer Berlin Heidelberg New York, 2005.

Sasaki, Y.: An objective analysis based on the variational method, J. Met. Soc. Japan, 36, 77-88, 1958.

Sasaki, Y.: Some basic formalism in numerical variational analysis, Monthly Weather Review, 98, 875-883, 1970.

Sharman C. A.: A mass-consistent model for wind fields over complex terrain, J. Appl. Meteor., 17, 312-219, 1978.