This is an **extended abstract** of the paper

Xie, H. and Yapa, P.D. (2003). "Simulating the Behavior and the Environmental Effect of Sediment Plumes from Deepwater Mining," *Journal of Advanced Marine Science Technology, AMTEC*, Tokyo, Japan, 9(1), 7-35.

Simulating the Behavior and the Environmental Effect of Sediment Plumes from Deepwater Mining

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Abstract

A model for simulating the behavior of sediment plumes from deepwater mining and their resulting environmental effect is presented. This paper contains the complete model formulation and scenario simulations. The sediment transport model includes both the near field (plume dynamics) and the far–field (passive advection–diffusion) phases. The model can handle both upward and downward releases. The model also takes into account the possible separation of sediments from the main plume. The model is three-dimensional and takes ambient current variations and stratification into account. For simulating the behavior of chemicals attached to sediments, three types of chemicals are considered: heavy metal, organic chemical, and mineral. The main difference between the different types is how the y partition between being attached to the sediments and dissolved in water. The model simulates the transport of chemicals attached to the sediment as well as the chemicals dissolved in water. The scenario simulations assess the effect on biological life due to entombment by deposited sediments. The light-attenuation and the resulting effect on photosynthesis in the water column due to sediments are also simulated.

Introduction

The interest in manganese nodule mining in offshore Japan has generated a significant interest in simulating the behavior of resulting sediment plumes in the water column and their environmental effects. In general, sediment plumes can be released upwards (e.g. due to momentum of the mining tool) or downwards at a higher up release station (e.g. mining residue discharge). Plumes generated from the releases of sewage, oil, and gases are buoyant and generally move upward. Sediment plumes are negatively buoyant. Sediment plumes that are initially released upwards, lose their momentum at some point and then start moving downwards.

In the initial stages a release behaves as a plume. During this period, the internal dynamic of the plume must be taken into account (near-field phase). From hereinafter, this paper refers to this dynamics phase as the plume. Sediment plumes generally have multiple species (particle sizes) with a variation of slip velocities. Slip velocity is the velocity difference between the plume fluid and the other phases present (e.g. sediment particles). This leads to two modeling complications: the possible separation of particles from the main plume must be taken into account; and the possibility of different sizes of particles separating at

different points in the plume must also be taken into account. Regardless of whether a plume is initially negatively or positively buoyant, the entrainment changes the density inside the plume as the plume progresses. In a stratified ambient condition, the plume is likely to reach a neutral buoyancy status. Beyond this point the plume dynamics are generally not important and the movement of the sediments can be modeled as far-field conditions. However, the different settling velocities of the different particles must be taken into account in modeling the sediment behavior under far-field conditions. When the sediment plume eventually reaches the ocean bottom or an obstruction, portions deposit and portions may move with the ambient current.

This paper presents a three-dimensional model to simulate the behavior of sediment plumes by taking into account all the processes described above. The model takes complete three-dimensional and time dependent variation of velocity, salinity, and temperature into account. Entrainment is computed using a unified formula (Yapa and Zheng, 1997) where the coefficients do not need to be changed from one simulation to another. The chemicals attached to the sediments can partition and dissolve in water. The model considers different chemical types and how they partition. The model simulates the transport of chemicals attached to the sediment as well as the chemicals dissolved in water. Chemical distribution in water column and the benthic layer are simulated. The light-attenuation and the resulting effect on photosynthesis in the water column due to sediments are also simulated. The model assesses the mortality of benthos due to mining using the simulated distribution of deposited sediment thickness.



Some Results

a)

b)

Fig. 7: Thickness of deposited sediment at the sea bottom at the end of disturbance. a) Measured (from MMAJ, 1994); b) Simulated (from the present model).



Fig. 8: Simulated thickness of deposited sediment at the sea bottom: a) 90 hours (\approx 4 days); b) 180 hours (\approx 8 days); c) 270 hours (\approx 12 days); d) 360 hours (15 days)



Fig. 11: Concentration distributions of chemicals in water column 5 meter above sea bottom on day 15



Fig. 12: Concentration distributions of chemicals in deposited sediment on day 15

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Summary and Conclusions

The formulation of a model to assess the environmental impact due to the release of sediments from deep-sea mining was presented in detail. The model was used to simulate cases where data were available and the model simulations were compared with observed data. The model was used to simulate several scenarios of interest to determine the environmental impact due to deep-sea mining.

The model can simulate both the plume dynamics and the far-field phase of the sediment releases. Multiple sediment particle sizes are considered in the model. Possible sediment separation from the plume when strong currents are present is considered. The effects of concentration and flocculation on settling velocity are both considered in the model. The model uses an integral Lagrangian control volume method for the dynamic phase and advection-diffusion equations with Random Walk method for the far-field phase. The model can simulate a plume that is released upwards from the sea bottom or released downwards from the water surface or anywhere in the water column. Releases from both fixed source and moving source can be simulated. The model can take into account temporal as well as spatial variations of ambient currents. This hydrodynamic information is provided as input to the model.

Two series of simulations for sediment transport were carried out. One is a simulation for JET experiment for 15 days. The other simulation assumes that sediment is disturbed for a long period (75 days) for a commercial mining, and the discharge condition is kept the same. The simulated thickness of deposited sediment 15 days after the JET experiment began shows that two thickness peaks appear at the two ends of the tracks. The result agrees well with the measured data. The simulated neutral buoyancy level of near-field dynamic phase is about 10 m above the sea bottom, which agrees well with the assumption made by Nakata et al. (1997). The simulated results show that larger particles deposit early and closer to the tracks of the disturber. Small particles suspend in the water column for a longer time and move with the ambient water and then deposit farther from the tracks. The concentration of suspended sediments in the water column has a zigzag pattern, which is influenced by the direction of ambient water and the reciprocating motion of the disturber. The 75-day simulation shows that the patterns of the deposited sediment are similar to the 15-day simulation. The thickness of deposited sediment increases obviously with time. However, no obvious increase of suspended sediment concentration occurs because of the motion of ambient water.

Sediments released usually contain chemicals attached to them. The ambient water may also contain some chemicals. Depending on the chemical, there is continuous exchange of chemicals between the sediment and the water through a process called "partitioning". Chemicals released from the sediments can be present in the form of "dissolved in water". The model presented here included the partitioning process. Different chemicals have different partitioning characteristics (e.g. a constant partition coefficient or a partition coefficient that depends on concentration). Lagrangian parcels are used to simulate the dissolved chemical transport in ambient water. To reduce the time consumed, multiple-sized grids are applied to simulate the transport of dissolved chemicals in water.

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Two series of simulations for chemical transport (one is 15-day simulation; the other is a 75-day simulation) were carried out. Heavy metal Cu and Pb, organic chemical TOC, and mineral $CaCO_3$ are selected for the simulations. The results from the 15-day simulation show that the concentration distributions of chemicals in water column are mainly determined by the distribution of sediment. All the chemicals have higher concentration near the tracks than far away and two concentration peaks appear at the end of the tracks. The results show a larger diffusion cloud of chemicals than the sediments due to the vertical velocity of sediments. The concentration of Cu is lower than Pb in water column and vice versa at the sea bottom because of the higher partition coefficient. The concentration distribution of organic carbon looks somewhat different from heavy metals Cu and Pb, because the partition coefficient of organic carbon between sediment and water is not a constant as in heavy metals. As the partition of CaCO₃ between water and sediments is negligible, the concentration distribution patterns of mineral CaCO₃ are the same as that of sediments in water column and at the sea bottom. The 75-day simulated results show that the concentrations of chemicals at the sea bottom are increasing continuously with time due to the accumulation of deposited sediment. However, no obvious increase of chemical concentrations is shown in water column from 15 days to 75 days because of the motion of ambient water.

Other environmental impacts due to deep-sea mining simulated are the acute mortality of benthos due to the thickness of deposited sediments. The concept of first order kill rate is used in the model. The model can be used to simulate different kinds of benthos. The simulated result shows that the damage to macrobenthos is not obvious, which agrees well with the conclusion from the acute mortality experiment. The mortalities of macrobenthos and meiobenthos both increase with time. The mortality of meiobenthos is always larger than macrobenthos. The results show that the mortality map shapes are affected by the pattern of sediment deposition. The model assesses light attenuation due to the surface discharge and its impact on photosynthesis as well. The simulation of light attenuation and impacts on photosynthesis are based on the relationships between sediment concentration, photosynthetically active radiation and net primary productivity in the euphotic zone. The simulated results show that the light intensity decreases faster in the areas where particulate concentration is high.

The model is developed based on the current available knowledge of the processes. The processes that define the environmental effect are based on limited theories and sparse data. Therefore, the model results should be viewed as estimates. However, the simulations are useful and show what can be done with a model to assess the environmental impact from deep sea mining. More studies are needed to find details on environmental effects due to sediment plumes from deep sea mining.