Modeling environmental impact on sediment caused by discharges deposited on the sea floor

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Abstract

A model has been developed that is able to model various types of impact on the sea floor caused by the deposition of particle matter and chemicals (attached to the particle matter). Particle matter may also contain heavy metals. The sediment is assumed to be represented by natural grains and porewater. The concentrations of dissolved chemicals in the pore water are assumed to be bioavailable, and the concentrations (toxicity) in the pore water are then given by partition of the chemicals (and heavy metals) between the pore water and the sediment. Other stressors caused by the discharges deposited are oxygen depletion (caused by the biodegradation of the chemicals deposited), generation of "exotic" sediment (caused by the particle size distribution of the particle matter deposited, which may have another distribution than the original sediment) and burial. All these factors are embedded into a numerical model that is able to simulate these stressors as a function of sediment location and time.

Keywords: sediment, environmental impact, numerical simulation, partitioning.

1 Introduction

This paper will focus on impacts on the sea floor caused by offshore discharges of drilling debris. Activities associated with offshore drilling operations lead to a variety of discharges with different durations and behavior in the recipient. Examples of the types of drilling muds used include WBM (*Water Based Mud*), SBM (*Synthetic Based Mud*) and OBM (*Oil Based Mud*). The discharges can take place from the drilling rig (when drilling deeper well sections) or directly to the sea floor (when drilling top well sections). Some constituents of the discharge are water-soluble chemical additives, which dissolve into the water column whilst others are particulates (cuttings and weight material like barite) or

WIT Transactions on Ecology and the Environment, Vol 111, © 2008 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/WP080311

highly lipophilic chemicals with a large log K_{ow} (octanol-water partition coefficient). Chemicals with sufficiently large K_{ow} values, may attach to particulate matter in the discharge. Heavy metals in barite may also cause environmental impacts in the sediment. Due to their particle content, the discharges will have a tendency to sink, and mineral particles typically separate from the discharge plume and sink to the sea floor. Therefore, the drilling discharges may cause impacts both in the water column and in the sediment. Sediment impacts can extend over long time scales (years) after the discharge period has ceased (UKOOA [1]), whereas the potentially harmful effects in the water column fade rather quickly after the end of the discharge period due to the dilution with the ambient water.

Numerical models describing the fate of chemicals and particles discharged to the sea during drilling have been developed and applied previously. However, these models are of different types and complexities. Some models incorporate environmental risks caused by the discharges, whilst some are limited to calculating the fate of the discharge (compounds) only. Other models focus on the actual deposits on the sea floor, without considering the actual processes within the sediment layer. Examples of models that do not include risks or processes in the sediment are described in Brandsma and Smith [2], Brandsma [3] and Rye et al. [4-6]. Other models have attempted to include the actual time development of the environmental risk for the sediment caused by drilling discharges (Sabeur et al. [7]). However, as highlighted in a review article by Khondaker [8], a comprehensive model that incorporates all of the essential processes and their resulting environmental risks in both the water column and sediments is lacking. The model presented in this paper accounts for how the stressors in the sediment are dealt with.

Meinhold [9] identifies the various impacts caused by drilling discharges that will be encountered in the sediment. Organic enrichment and toxicity both contribute to oxygen depletion (anoxia) within sediments. These stressors have also been incorporated in the development of the present model. In addition, Meinhold [9] discusses the physical effects of the material deposited. This includes burial effects and changes of grain size caused by deposition of particles with diameters differing from the natural grain size at the drilling site. These effects have therefore been included in the development of the present model.

2 Deposition of drilling discharges on the sea floor

When drilling debris is discharged to the sea, the particles will tend to sink to the sea floor. Chemicals with large partition coefficients K_{ow} will tend to adhere or attach to the particle matter and thus follow the particles down on the sea floor. The sinking velocities of the particles can be divided into two regimes, the *Stokes* regime and the *constant drag* regime. The sinking velocities within the *Stokes* regime for smaller particles are given by eqn. (1):

$$W_1 = \frac{d^2 g'}{18\upsilon} \tag{1}$$

where W_l is laminar Stokes sinking velocity of a particle, d is the particle diameter, g' is the reduced gravity = $g(\rho_{particle} - \rho_{water}) / \rho_{water}$, g is the standard gravity, ρ is the density of the particle or sea water and $\upsilon =$ kinematic viscosity = 1.358 x 10^{-6} m^2/s at 10 °C.

The second regime for sinking particles is the friction-dominated *constant drag* regime for larger particles. A general expression for this sinking velocity can be derived from the balance between buoyancy forces and drag forces acting on the particle (Hu and Kintner [10]) calculated by eqn. (2).

$$W_2 = \sqrt{\frac{4}{3}\frac{d\,g'}{C_D}} \qquad (2)$$

The drag coefficient C_D in this equation is a function of the Reynolds number ($\mathrm{Re} = W_2\, d / \nu$). These two asymptotic regimes can be combined into a single interpolation function (eqn. (3), Johansen [11]):

$$\mathrm{W} = \frac{1}{\left(\frac{1}{W_1} + \frac{1}{W_2}\right)} \qquad (3)$$

The empirical drag coefficient in eqn. (2) is chosen so that correspondence is reached between the friction dominated sinking velocity as given in U.S. Army Coastal Engineering Manual [12] and the eqn. (2) above. This formula takes into account that grains are usually non-spherical and have therefore generally lower sinking velocities than grains with spherical shapes.

A graphical presentation of the curve shape given by eqn. (3) is shown in Figure 1. For low diameter particles (diameters lower than 2 x 10^{-4} m), the formula corresponds well with the Stokes sinking velocity. For larger particle diameters (diameters larger than 2 x 10^{-3} m), the formula corresponds well with the friction dominated velocity. In the diameter range in between, the sinking velocities are influenced by contributions from both regimes.

The resulting deposition on the sea floor will thus be distributed geographically on the sea floor, dependent on the sinking velocity and the (time and space dependent) ocean currents in the area (which are also utilized in the numerical simulations). Figure 2 shows an example of deposition on the sea floor calculated with the numerical model.

3 Fate of the drilling debris on the sea floor

Processes are taking place in the sediment that acts upon the fate of the chemicals and the particle matter that have deposited on the sea floor. Bioturbation causes the debris to mix with the natural sediment. Partition of the chemicals between the pore water and sediment causes parts of the chemicals to dissolve in the pore water. One approach to describe these processes is the use of the so-called "diagenetic equations". These are differential equations that have

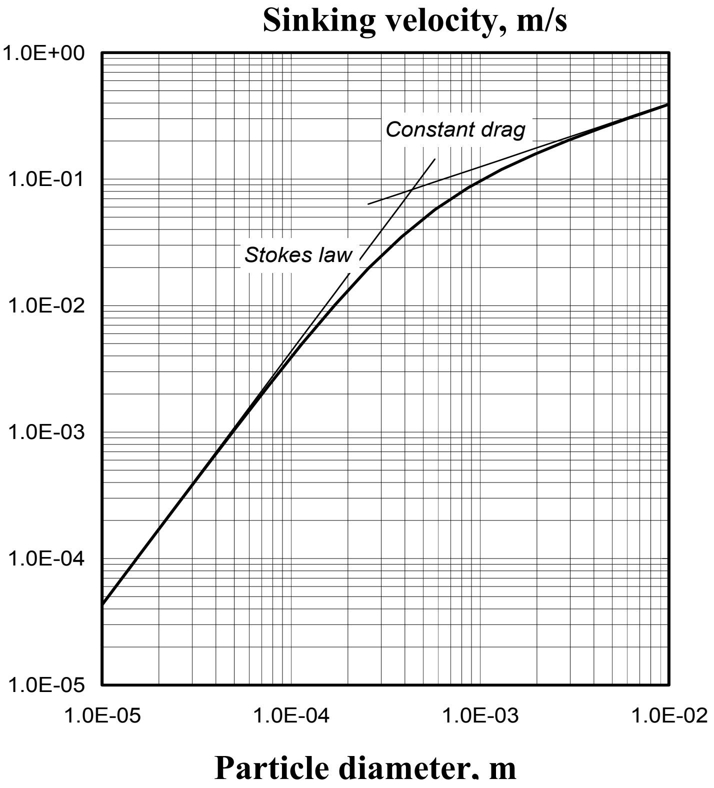

Figure 1: Particle size dependent variation in fall velocity of mineral particles (cuttings) in seawater. Solid density 2500 kg/m^3. Thin lines: Stokes law and constant drag law according to eqns. (1) and (2). Thick line: Interpolation formula (3).

to be solved numerically. One example of such an equation can be written as eqn. (4) (simplified version):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(D \ \frac{\partial C}{\partial z} \right) - K_C \ C + Q_C \tag{4}$$

where the two last terms on the right hand side are reaction or source terms. The first term on the right hand side is a diffusion term (could represent bioturbation in the sediment or molecular diffusion through pore water), while the term on the left hand side expresses the rate of change of the concentration C (which could be a chemical, organic matter in the sediment, free oxygen in the pore water or some content of solid matter in the sediment). The equation can be used for both compartments (pore water and sediment). The equation(s) can be used in its 1-dimensional form (vertical co-ordinate z included only), but has then to be solved for each horizontal grid cell on the sea floor (as shown in Figure 2).

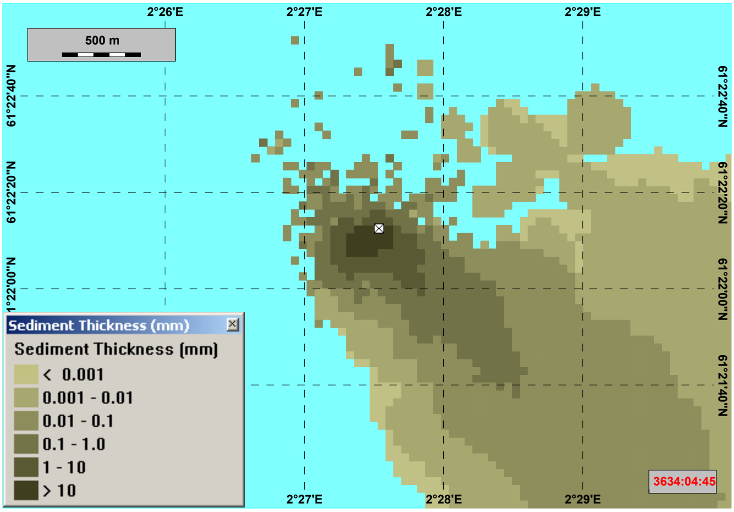

Figure 2: Example of a calculation of the geographical distribution of the deposition of cuttings and drilling mud (particles and chemicals attached to the particles) on the sea floor. The spreading on the sea floor is caused both by a variable grain size and a (time and space) variable ocean current.

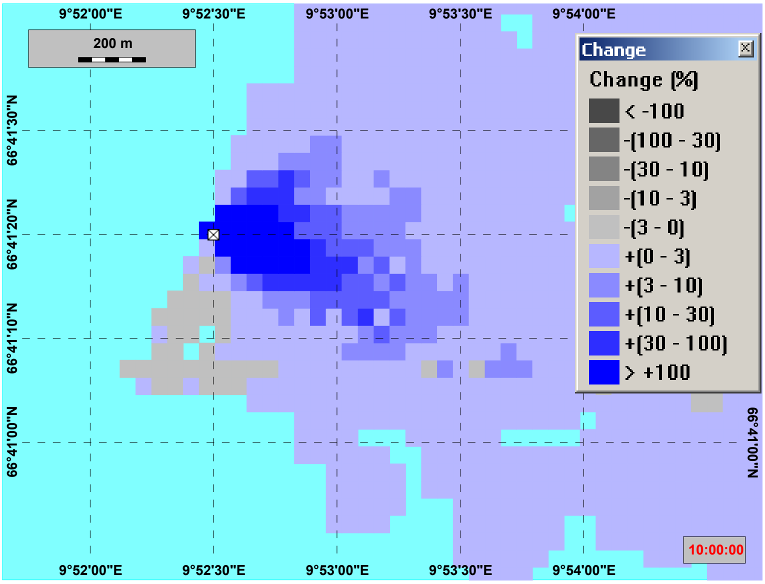

Figure 3: The % change of pore water oxygen content in the sediment layer (integrated over 10 cm sediment depth). The % change is expressing the change compared with the content of oxygen before discharge (natural content of oxygen in the sediment). Example calculation.

The model developed is denoted DREAM (*Dose related Risks and Effect Assessment Model*). Model documentation is presently available at the web site [13]. A publication on the use of the "diagenetic equations" for assessment of impact in the sediment is available at [14]. As an example, Figure 3 shows a calculation of the oxygen depletion in the sediment, caused by a discharge of drilling mud with chemicals attached to the particles in the discharge. The oxygen depletion in the sediment is caused by the biodegradation of the chemicals in the sediment. This biodegradation consumes the free oxygen present in the pore water. For this particular application, two diagenetic equations are used, one for the free oxygen in the pore water and one for the distribution of the chemical to be biodegraded in the sediment.

4 The bioturbation coefficient

One of the factors that are important for the simulating the vertical distribution of the drilling debris in the sediment is the bioburbation coefficient. This factor simulates the intensity of mixing within the sediment layer, caused by the burrowing organisms present. The expression of the bioturbation mixing coefficient can be written as

$$D_B(z) = 3\,D_{Bave}\left(1-\frac{z}{L}\right)^2 \tag{5}$$

where D_{Bave} is the average bioturbation coefficient over the bioturbated layer depth L, denoted the bioturbation depth. The equation expresses that the bioturbation coefficient is at maximum at the sediment surface, and decays to zero at the sediment depth denoted L. Experience shows that the parameter L is on the average close to 10 cm, but may show large variations (Boudreau [15]). The value of L appears to be invariant for varying water depth (Boudreau [16]) and for varying natural burial velocities w (Boudreau [15], chapter 4.2).

The average bioturbation coefficient D_{Bave} however, has been shown to vary with the natural burial rate w. Sediment is naturally receiving (organic and inorganic) particles from the sea water above, which constitutes the main source of food for the organisms present in the sediment. An increasing burial rate w enhances therefore the bioturbation activity. The relation

$$D_{Bave} = 15.7\,w^{0.6} \tag{6}$$

is used (Boudreau [15], chapter 4.2), which is based on a best fit line drawn through data collected from a large variety of different oceanic conditions. w is here given in cm/year and the bioturbation coefficient is given in cm^2 per year. Since the burial rate is also depth dependent (w generally decays with an increasing depth), the bioturbation coefficient also becomes depth dependent, with decreasing values with increasing depth.

5 The irrigation factor

One factor that is presently not built into the DREAM model system is the irrigation factor. This is a factor that is able to enhance the vertical diffusion of dissolved compound in the pore water back to the sea water. The reason for this enhancement is the presence of bioturbators in the sediment whose activities will tend to increase the vertical exchange of pore water in the sediment with the sea water above.

There are laboratory and field experiments reported in the literature which show that the flux of dissolved matter from the pore water in the sediment to the water masses above may increase with a factor of order 10 or so when bioturbating organisms are included in the experiments, compared to the experimental results carried out without the presence of the bioturbating organisms. As examples, Berelson et al. [17] find an enhanced flux by a factor of 3 – 16 times the diffusion generated flux by carrying out chamber-measured radon fluxes in the field. Schaanning et al. [18] find that the diffusive flux is enhanced by a factor of 3 – 5 for some toxic compounds when comparing results from laboratory experiments carried out with and without the presence of bioturbating organisms.

The experimental evidence seems to be rather convincing that there is in fact present an enhanced flux from sediment to sea, compared to the diffusive transport generated by molecular diffusion alone. The numerical model is therefore planned to be extended to be able to account for irrigation phenomena, in addition to the molecular diffusion (in the pore water compartment).

6 Summary of results

A model has been developed denoted DREAM (*Dose Related Risk and Effects Assessment Model*) that is able to describe the fates of particle matter and chemicals deposited on the sea floor. The model is developed for the purpose of simulating impacts of various kinds on the sea floor (toxicity, oxygen depletion, grain size change and burial). The model has so far been based on physical/chemical properties of the discharge and the sediment, without taking into account the actual composition of the biota on the sea floor. As examples, the diffusion of chemicals dissolved in the pore water has so far been based on the molecular diffusion of the matter dissolved. However, the presence of biota may also enhance the molecular diffusion (as well as representing the origin for the bioturbation). The DREAM model will therefore be developed further to include additional diffusion in the pore water caused by the presence of biota (denoted irrigation).

Acknowledgement

The research and development activities described in the present paper are supported by the Norwegian Research Council under the program “Havet og Kysten”, PROOF part program, The PEIOFF project, headed by NIVA (*The Norwegian Institute for Water Research, Oslo, Norway*).

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