Numerical modelling of the petroleum oil penetration into sandy beach sediments

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Abstract A numerical model describing the penetration of petroleum oil into sandy beach sediments was developed to assess the behavior of stranded oil at tidal zone as a result of tanker accidents, and so on. To understand the penetration behavior, penetration rate of three species of petroleum oil (two species of fuel oil C and one species of crude oil) was observed experimentally with artificial tidal zone equipment. As a consequence, two types of oil were distinguished from the viewpoint of penetration rate. One (fuel oil C-1) kept its homogeneity in composition and showed relatively rapid penetration, the other (fuel oil C-2 and crude oil) became heterogeneous and slow in penetration. Considering this aspect as the adsorption of the polar compounds (i.e. asphaltenes) on the sediment surface, a numerical model that described oil penetration into sandy beach was developed. As a result, the difference in penetration rate between these two types of oil could not be replicated sufficiently only by consideration of the adsorption. However, the change of a parameter value which represents the apparent viscosity of oil led to good agreement with observations. Simulation results indicated that when fuel oil C or crude oil used in this study was stranded at a sandy beach located in Hiroshima Bay, Japan, 2 to 39% of total stranded oil might penetrate into the deeper zone (>3 cm in depth) over 50 days.

Keywords Numerical model; petroleum oil penetration; sandy beach

Introduction

A huge amount of petroleum oil has been spilled as a result of tanker accidents (e.g. Elliott and Jones, 2000) and so on. The spilled oil penetrates into sediments, and remains for a long period, e.g. more than 25 years (Wang et al., 1998). The spilled oil at a coastal zone affects the shoreline biota via the sediments and the interstitial waters revealing that the oil penetration into sandy beach sediments causes serious damage to the coastal zone ecosystem. That is why we should understand the penetration behavior of spilled oil to assess the influences on the ecosystem.

There are some numerical models that describe the oil spill (e.g. Reed et al., 1999), however, these models did not deal sufficiently with the oil penetration. While we can find some models that dealt with multiphase flow in sediments (e.g. Miller et al., 1998), these models considered the oil as a homogeneous fluid. In the micro-scale consideration, the fluid characteristics can be changed with the change of its chemical composition.

In this study, we perform a series of experiments that demonstrate the petroleum oil penetration into artificial tidal zone sediment to clarify the relationship between the compound change of petroleum oil and penetration rate. Then, a numerical model that describes the oil penetration at a sandy beach is proposed based on the experimental result. Finally, using this model, the penetration of some petroleum oils into actual tidal flat sediments are predicted.

Experiments

Figure 1 shows the experimental apparatus and conditions. Acrylic plastic columns were filled with glass beads which mimic the sandy beach sediment, and were placed in a water
butter, where the water level was varied to replicate the tidal action on a sandy beach. The tidal condition was set based on the aspect of tide in Hiroshima Bay, Japan. Three species of oils, i.e., crude oil (Upper Zakum Crude Oil, 20 cP in viscosity), and two types of fuel oil C (fuel oil C-1, 2100 cP, and fuel oil C-2, 2200 cP) and three sizes of glass beads, namely 1 mm, 0.6 mm, and 0.25 mm in diameter, were used. Three mL of oil (equivalent to 1.2 L-oil m−2-beach surface) was applied to the top of the column when the water level was maximum, then the tidal action was continued. The sediments were collected at a certain depth with time elapsed being 50 days, and the petrol hydrocarbon contents (PHC) was measured with a TLC-FID detector (Iatro-Scan TH-10, Diatron Co. Ltd.) (Goto et al., 1994). Furthermore, asphaltenes and maltenes was measured separately with the heptane precipitation method. Thus, total PHC means the sum of PHC of asphaltenes and maltenes, and asphaltene-PHC means the PHC measured as asphaltenes.

Figure 2 shows the penetration rates of total PHC and asphaltene-PHC as a function of oil species. The penetration rate was estimated with the first-order elimination constant of them from the surface zone (assumed as <3 cm in depth) to the subsurface zone (>3 cm in depth). In this estimation, evaporation to the atmosphere and elution to the seawater were ignored. The penetration rate of total PHC in the case of fuel oil C-1 was about six times as fast as that of fuel oil C-2 in spite of the similar viscosity, while the penetration rate of crude oil was almost equal to that of fuel oil C-1 in spite of the large difference in viscosity (ca. 100 times) between them. On the other hand, there was little difference between the penetration rate of total PHC and asphaltene-PHC in the case of fuel oil C-1, indicates that this oil kept its homogeneity during penetration. The asphaltenes penetration rate of fuel oil C-2 and crude oil was about 30% and 76%, respectively, of the total PHC penetration rate, indicating that the heterogenation of the compounds was occurring in these cases. These results suggested that the penetration rate of oil into sandy beach was dependent strongly on

**Figure 1** Artificial tidal zone equipment

**Figure 2** Penetration rate of total oil and asphaltene as a function of oil species
the possibility of the heterogenation of compounds rather than on the initial viscosity. It can be thought that the polar compounds can be adsorbed easily on a mineral surface. This aspect was reflected in the model development described later.

**Numerical model**

Table 1 shows the model equations and parameters. In this model, the high-polarity compounds and low-polarity compounds of petroleum oil were considered as the state variables (Eqs (1) and (2)). The definition of these two compounds was the capability of adsorption on the sediment surface. It was assumed that only the high-polar compounds were able to adsorb on the sediment surface. The penetration rate \( u \) should be affected by the oil viscosity, sediment porosity and specific surface area, and the head loss of the oil. The relationship is described with Kozeny’s equation (Eq. (5)) (Carman, 1937). The head loss was calculated based on the tidal velocity, and other parameters except for \( a \) were determined with actual measurements.

As shown in Figure 3, parameter \( a \) was calibrated as 100 for the fuel oil C-1 which did not show the heterogenation. This result indicates that overall the fuel oil C-1 penetration into glass beads of 0.25–1 mm diameter was replicated fairly well by the proposed model. Using this value, the penetration behavior of fuel oil C-2 and crude oil into glass beads of 1 mm in diameter was predicted. The results are shown with the thin lines of Figure 4. This reveals that the calculation with \( a = 100 \) gives the overestimates of penetration for both fuel oil C-2 and crude oil. Then, to replicate the measurement, we re-calibrated the parameter \( a \). As a result, \( a = 1 \) gave feasible predictions for both fuel oil C-2 and crude oil, which are shown in Figure 4 with the thick lines.

<table>
<thead>
<tr>
<th>Equations</th>
<th>Parameters</th>
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<tr>
<td>( \frac{\partial C_H}{\partial t} = u \cdot \frac{\partial C_H}{\partial z} - \frac{\partial q_H}{\partial t} )</td>
<td>( C_H^{*} ) : adsorption-equilibrium concentration of the high-polar compounds [g g(^{-1})]</td>
</tr>
<tr>
<td>( \frac{\partial C_L}{\partial z} )</td>
<td>( C_L ) : concentration of low-polar compounds in the bulk sediments [g g(^{-1})]</td>
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<tr>
<td>( \frac{\partial q_H}{\partial t} = K_F \cdot a_v \cdot (C_H - C_H^{*}) )</td>
<td>( K_F ) : total mass transfer coefficient [s(^{-1})] (1  × 10(^{-4})) (Pernyeszi et al., 1998)</td>
</tr>
<tr>
<td>( q_H = \frac{\beta}{C_H^{*}} )</td>
<td>( a_v ) : proportional coefficient [-]</td>
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Table 1  Model equations and parameters
Using this model, we performed a simulation to clarify the stranded oil penetration into a calm sandy beach (so called “tidal flat”) in the Hiroshima Bay, Seto Inland Sea, Japan. The tidal flat sediment contains a certain amount of silt (particles less than 0.075 mm in diameter). The silt has a relatively large surface area and should reduce the oil penetration with its flow resistance. In this model, however, the particle distribution was not considered. Thus, the effects of silt content on oil penetration were estimated in terms of the equivalent surface area. The silt content and median particle size of simulated tidal flat were 3.5% and 0.6 mm, respectively, after Lee et al. (1997). From these values, the specific surface area

**Figure 3** Comparison between model calculation and measurements of fuel oil C-1 penetration

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was calculated as 250 [cm$^2$ cm$^{-3}$]. The equivalent particle size to this specific surface area is 0.048 [cm], and we used this value in the simulation. The stranded oil species and volumes were set as the same as the experiments.

Figure 5 shows the calculation of the time course of the ratio of penetrated oil into the subsurface zone (>3 cm in depth) to total stranded oil, and the vertical profiles of three oils at 50 days after the start of penetration. In the 50 days after stranded, the percentages of penetrated oil into the subsurface zone were calculated as 39%, 31% and 2% for crude oil, fuel oil C-1 and fuel oil C-2, respectively, while the penetration depth of the crude oil is the deepest in these three oils. The oil with more than 0.1 g-oil g$^{-1}$-sediment were found even in 16.1 cm in depth in this case, while the penetration depth decreased in the order of fuel oil C-1 and C-2. The maximum depth where the oil concentration was calculated more than 0.1 g-oil g$^{-1}$-sediment were 9.8 cm and 4.4 cm, respectively, for the fuel oil C-1 and C-2.

**Discussion**

The experiment revealed that the examined oil was divided into two types, namely “heterogenation” and “non-heterogenation” oils, based on composition changes in the penetration process. The fuel oil C-1 was the former type, and the fuel oil C-2 and the crude oil were the latter type. The parameter fitting revealed that the parameter $a$ was different for these two types of oils. For the non-heterogenation oil, $a = 100$ gives the most feasible calculation, while $a = 1$ gave the good prediction for the heterogenation oil. Eq. (5) means that the parameter $a$ is in inverse proportion to the viscosity. Thus, the apparent viscosity of two types of oil in the glass beads was different. The apparent viscosity of the heterogenation oil was about 100 times as high as that of the non-heterogenation oil. The heterogenation is caused by the preferential adsorption of asphaltenes or other polar compounds in the oil on the sediment surface, which is included in the numerical model. However, as shown in Figure 4, the deceleration in penetration rate of the heterogenation oil cannot be described only with the adsorption. Other mechanisms may account for this deceleration.

One view is that the wettability of the solid surface is changed with the adsorption of compounds. The adsorption of asphaltenes or other polar organic compounds onto the solid surface can change the wettability of the surface from the water-wet to the oil-wet (Standal et al., 1999), and as a result, the affinity of the oil to solid surface becomes high and the penetration rate of oil should be decelerated. To understand this mechanism quantitatively, we should clarify the adsorption dynamics of polar compounds. There are some papers describing the adsorption of oil components onto solid surfaces (e.g., Daughney, 2000), however, the adsorption from the bulk oil phase was not considered in these studies. This circumstance indicates that it is difficult to model the adsorption dynamics of compounds from bulk oil onto solid surface in detail.
The other possible mechanism is the emulsification of oil as a result of the adsorption of polar compounds on the water-oil interface (McLean and Kilpatrick, 1997), and makes a rigid film like the oil continuous emulsion. This film gives resistance to oil penetration, and as a result, the apparent viscosity of oil is increased. However, the emulsification mechanism is highly complicated.

As mentioned above, the proposed model may be not enough to describe the oil penetration into sandy beach from the viewpoint of surface action in detail. However, from the standpoint of prediction of the oil penetration rate, the model can calculate the whole tendency of oil penetration with changing a parameter. As a consequence, there is considerable validity in the employment of this model as an assessment tool for oil penetration at sandy beach.

**Conclusion**

In the case of oil penetration into sandy beach sediments due to tidal action, two types of oil were distinguished. One kept its homogeneity in composition, and the other became heterogeneous during penetration. The penetration rate of the latter case was obviously decelerated and the penetration depth was shallow. Considering this aspect as the adsorption of the polar compounds (i.e. asphaltenes) on the sediment surface, a numerical model that described oil penetration into sandy beach due to tidal action was proposed. As a consequence, the deceleration behavior could not be replicated sufficiently only by consideration of the adsorption. However, the change of a parameter value, which represents the apparent viscosity of oil, led to giving good agreement with observations. Simulations using this model predicted that when fuel oil C-1, fuel oil C-2, or crude oil used in this study are stranded at a calm sandy beach (so called tidal flat) located in Hiroshima Bay, Japan, 31%, 2%, or 39% of stranded oil, respectively, might penetrate into the deeper zone (> 3 cm in depth) during the 50 days after stranding.

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**References**


