MIKE Zero

Non-Newtonian Fluids in MIKE Zero Rel2017 SP1

Note
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1 Non-Newtonian Fluids in MIKE Zero Rel2017 SP1

The hydrodynamic solver in MIKE 21 HD FM, MIKE 21 Classic and MIKE 21C has been extended with a Mud, Debris or Oil feature targeting simulation of one-phase flows with different flow characteristics than clear-water, e.g. oil or water with high concentrations of debris or mud.

2 General Description

The ‘Mud, Debris or Oil’ feature enable an alternative hydrodynamic solution in which a fluid dependent flow resistance is added to the standard flow momentum equations.

Naef et al (2006) defines a number of formulations for calculating flow resistance relations and the flow resistance term, $\tau_0/\rho$. The current implementation include a ‘Full Bingham’ relation, which in addition allows for applying simpler resistance formulations excluding the Bingham viscosity term (e.g. the ‘Turbulent and Yield’ relation as defined in Naef et al, 2006).

The full Bingham flow resistance relation determine the flow resistance term ($\tau_0/\rho g h$) from the following third order equation (see Naef et al, 2006):

$$2\tau_0^3 - 3 \left( \tau_y + 2 \frac{\mu_B q}{h^2} \right) \tau_0^2 + \tau_y^3 = 0$$

where:

- $q$ is the flux (discharge per unit width)
- $h$ is the fluid depth
- $\tau_y$ is the yield stress
- $\mu_B$ is the Bingham fluid viscosity

The third order equation is solved numerically during the simulation to give $\tau_0$ as function of the yield stress ($\tau_y$), Bingham viscosity ($\mu_B$), water depth ($h$) and flux ($q$).

Note, that it is possible to activate e.g. the Turbulent and Yield resistance formulation by simply setting the Bingham Viscosity parameter, $\mu_B$, equal to zero.

2.1 Simulation results, examples

An example for illustrating the effect of activating the Mud, Debris and Oil feature is shown in Figure 2.1. The total flood extent during simulation for water without any mud or debris (‘Clean Water’) is presented together with results from two scenarios with different Fluid parameter definitions (Low and High concentration Mud flows).

This model example simulate a dam breach with a sudden, large release of water. The release point is located in the lower left corner of the 2D model and the fluid travels downstream of the river in direction towards the upper right corner of the model domain. The example illustrate that fluid characteristics defined by the three variables; Density, Yield stress and Bingham viscosity does impact significantly the potential extent of a flood wave when the fluid contain a certain concentration of mud or debris.
Choosing Mud/Debris/Oil Model Parameters

The rheological properties of non-Newtonian fluid are driven by the complex interaction of a fluid’s chemical and material composition. Key composition properties include the particle size distribution (e.g. percent fines), solids concentration, water content, chemical composition, and mineralogy such as the presence of clay minerals.

The Bingham rheological model is well suited for homogenous fluid mixtures with high concentrations of fine particles (e.g. mudflows, hyper-concentrations of fine sand, silt, and clay-size sediment) and other material types such as oils.

The key parameters for the Mud/Debris/Oil model in MIKE FM, MIKE 21 Classic and MIKE 21C are the following (default unit shown in brackets):

- **Fluid density**: Density the fluid mixture [kg/m³]
- **Yield stress**: Shear stress threshold that needs to be exceeded for the fluid to flow [Pa]
- **Dynamic viscosity**: Dynamic viscosity of the Bingham fluid mixture [Pa·s]

### 3.1 Fluid density

The fluid density can be determined from either measurements of the fluid to be modelled or calculated using the solids concentrations of the fluid mixture.

### 3.2 Yield stress

Ideally, the yield stress (i.e. yield strength) of the fluid to be modelled can be determined from rheograms developed from viscometric measurements in a laboratory. A rheogram relates the shear rate of the fluid to the applied shear stress. A commercially available concentric cylindrical viscometer is ideally suited for this type of analysis because it is capable of developing the rheogram for a wide shear rate range. However, laboratory derived rheological analyses may not always be possible or practical.
Yield stress can also be determined empirically from both case studies involving similar fluid compositions and empirical relationships. For hyper-concentrations composed of fine sediment, yield stress is often formulated as a function of material type (e.g. clay mineralogy) and sediment concentration. Julien (2010) provides the following recommended empirical relationships for yield stress as a function of sediment concentration for a variety of material types using this exponential form:

$$\tau_y = a \cdot 10^{b \cdot C_v}$$

where:
- $\tau_y$ is the yield stress [Pa]
- $a, b$ are coefficients (see Table 1)
- $C_v$ is volumetric sediment concentration

Table 3.1 Coefficients for yield stress empirical relationships from Julien (2010)

<table>
<thead>
<tr>
<th>Material</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite (montmorillonite)</td>
<td>0.002</td>
<td>100</td>
</tr>
<tr>
<td>Sensitive clays</td>
<td>0.3</td>
<td>10</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>0.05</td>
<td>9</td>
</tr>
<tr>
<td>Typical soils</td>
<td>0.005</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Oils are a special application where the yield stress is typically set to zero and the dynamic viscosity dictates the laminar flow nature represented by the Bingham rheological model. For zero yield stress the Bingham fluid model is valid for laminar depth-integrated flow.

Note that the typical exponential relationship between yield stress and sediment concentration indicates that at some point small changes in concentrations can dramatically change yield stress. This is an important dynamic sensitivity to consider when evaluating Bingham fluids.

### 3.3 Fluid dynamic viscosity

Once the fluid is in motion, the dynamic viscosity (i.e. plastic viscosity) represents how the fluid flows under applied shear stresses. Similar to yield stress, the dynamic viscosity can be determined from rheograms developed from viscometric measurements in a laboratory. However, laboratory derived rheological analyses may not always be possible or practical.

Dynamic viscosity can also be determined empirically from both case studies involving similar fluid compositions and empirical relationships. Julien (2010) provides the following recommended empirical relationships for yield stress as a function of sediment concentration for a variety of material types using this exponential form:

$$\mu_m = 0.001 \cdot 10^{c \cdot C_v}$$
where:
\[ \mu_m \] is dynamic viscosity [Pa·s]
\[ c \] is a coefficient (see Table 2)
\[ C_v \] is volumetric sediment concentration

<table>
<thead>
<tr>
<th>Material</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite (montmorillonite)</td>
<td>100</td>
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<td>7.5</td>
</tr>
</tbody>
</table>

Table 3.2 Coefficients for dynamic viscosity empirical relationships from Julien (2010)

For modelling viscous, low-strength fluids such as oils, the dynamic viscosity is the key parameter for the Bingham model as the yield stress is often set to zero. The dynamic viscosity for such materials is best determined from rheograms developed from viscometric measurements in a laboratory, e.g. commercially available concentric cylindrical viscometer. Available literature (e.g. product descriptions) and case studies for commercially derived materials are other appropriate sources for choosing the value for the dynamic viscosity parameter.

4 References


