

# Experimental study on the critical initiation of reservoir fluid mud motions

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**Abstract:** Reservoir fluid mud is the stagnant or near-stagnant suspension distributed at the bottom of a reservoir after variable-density flows. It consists of fine particles that flocculate easily, and its thickness can be maintained unchanged over a long time period. Because the formation and the movement of reservoir fluid mud are affected by various factors, and given that measured data relevant to the dynamic conditions of the reservoir fluid mud are lacking, current results can hardly explain scientific questions that have to be resolved. These include the development of reservoir fluid mud and its response mechanisms to subsequent floods. In this study, a pressurized sealed water flume is employed to simulate deep-water conditions and to facilitate the conduct of experiments on the initiation of reservoir fluid mud motions. The results demonstrate that the critical shear stress required for the initiation of motion of fluid mud increases exponentially as a function of the volumetric weight of fluid mud and water depth. The critical shear stress is much smaller than the Bingham yield stress and the two are associated according to a power-function relationship. The findings provide technical support for the utilization of the reservoir fluid mud and the optimization of reservoir operations.

## 1 Introduction

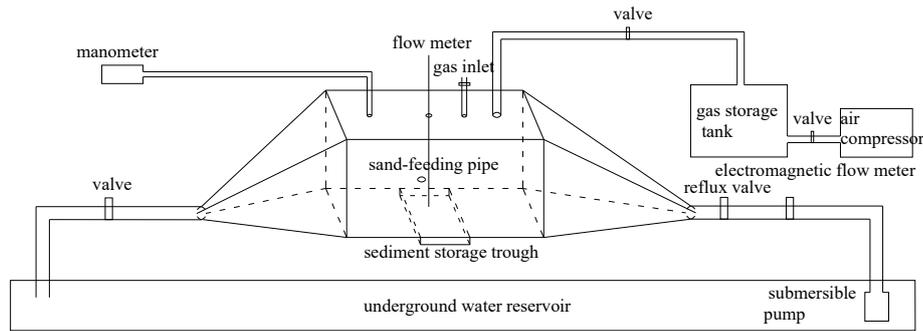
Reservoir fluid mud is the stagnant or near-stagnant suspension at the bottom of a reservoir which is generated as a result of variable-density flows. It is composed of fine grains that flocculate extremely easily. Its thickness can remain consistent over a reasonably long period of time. Because there are various factors influencing the formation and the movement of reservoir fluid mud, and because measured data closely associated with the dynamic conditions of the reservoir fluid are limited, current research results can hardly support analyses on pending scientific problems, such as the development of reservoir fluid mud and its response mechanisms to subsequent floods. A pressurized sealed water flume is used in this study to simulate deep-water conditions based on which several experiments on the initiation of motions of the reservoir fluid mud are performed. The findings can provide a technical foundation for the utilization of reservoir fluid mud and the optimization of reservoir operations.

## 2 Experimental flume

The setup of the pressurized flume is illustrated in Figure 1. The flume is 4.5 m long, 0.4 m wide and 0.8 m high. It mainly consists of seven parts: (1) an air compressor, a gas storage tank and valves to maintain stable pressures, (2) a pressure gauge and an outlet vent to adjust the pressures into and out of the flume in real time (to simulate water pressures), (3) a submersible pump, an electromagnetic flowmeter and a check valve to control the water flow at the inlet, (4) a sediment inlet pipe and a sediment-covered trough (1.0 m long, 0.4 m wide, and 0.05 m deep) to store the experimental sediments, and a sampling hole located downstream of the sediment-covered trough at 0.05 m to measure the sediment concentration in water, (5) valves to control the water flow at the outlet, (6) an electromagnetic flowmeter to measure the vertical flow velocity above the sediment-covered trough in real time, (7) an underground water reservoir to maintain the circulation of water used in the experiment.

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**Fig. 1** Schematic of the pressurized water flume

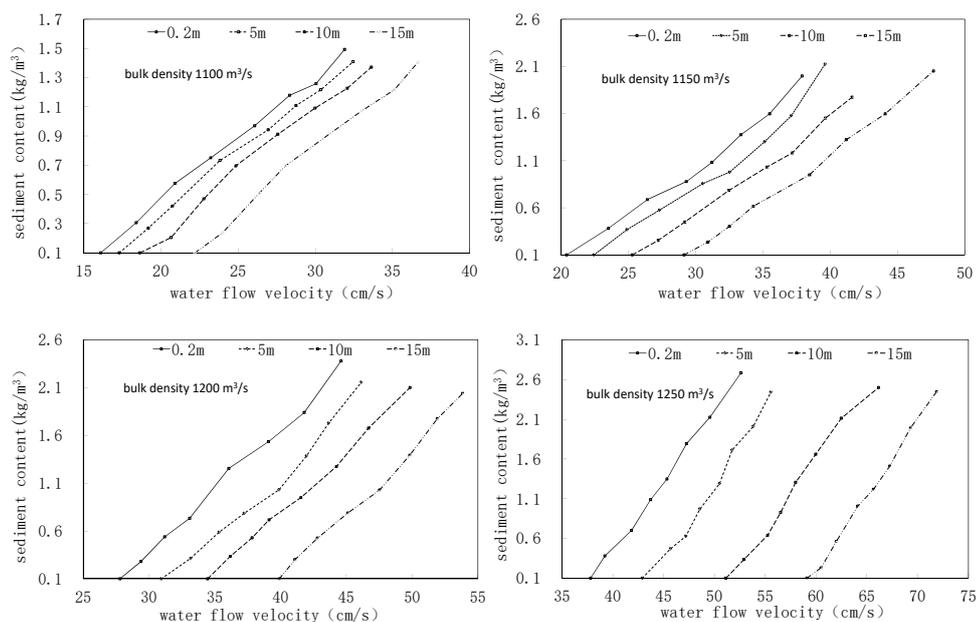
### 3 Experimental conditions

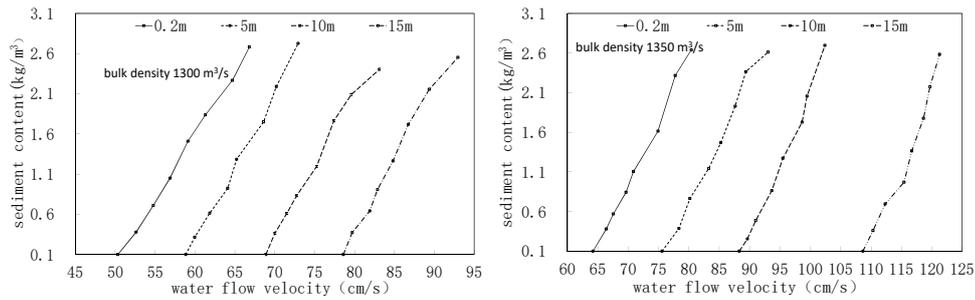
- (1) Sediment samples: The fluid mud from the dam area of the Xiaolangdi reservoir with a mean particle diameter of 0.006 mm was used.
- (2) Initial volumetric weights of fluid mud: 1100, 1150, 1200, 1250, 1300, and 1350 kg/m<sup>3</sup>. Before the experiments, fluid mud was stirred to make it homogeneous, and it was then evenly distributed in the sediment-covered trough that was located in the middle of the water flume.
- (3) Initial fluid mud thickness: 5.0 cm.
- (4) Initial water depth of the flume: 0.2 m.
- (5) Flow conditions: The water flow during the experiment was gradually increased until significant fluid mud motions were noted.
- (6) Simulated water depth: 0.2, 5, 10, and 15 m.

Figure 2 shows the variations in the suspended sediment concentration with flow velocity for the initial fluid mud volumetric weights of 1100, 1150, 1200, 1250, 1300, and 1350 kg/m<sup>3</sup>, and water depths of 0.2, 5, 10, and 15 m. It is noted that under the action of water flows, the flow velocity of the fluid mud with a mean particle diameter of 0.006 mm was closely associated with the initial volumetric weight. A larger initial volumetric weight led to a higher initiation flow velocity. The initiation flow velocity was also positively correlated to the water depth. Figure 2 shows the variations in the suspended sediment concentration with flow velocity for the initial fluid mud volumetric weights of 1100, 1150, 1200, 1250, 1300, and 1350 kg/m<sup>3</sup>, and water depths of 0.2, 5, 10, and 15 m. It is noted that under the action of water flows, the flow velocity of the fluid mud with a mean particle diameter of 0.006 mm was closely associated with the initial volumetric weight. A larger initial volumetric weight led to a higher initiation flow velocity. The initiation flow velocity was also positively correlated to the water depth.

## 4 Results

### 4.1 Flow velocity and critical shear stress for the initiation of fluid mud motion

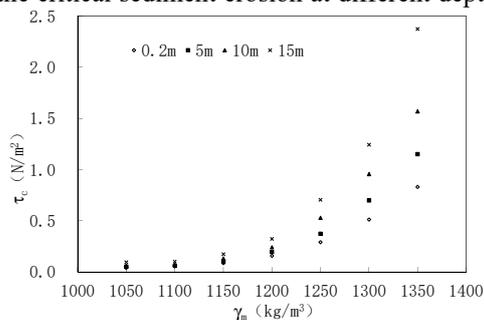




**Fig. 2.** Variations in the suspended sediment concentration as a function of flow velocity for different initial fluid mud volumetric weights at different water depths

#### 4.2 Relationships of the critical initiation shear stress with volumetric weight and water depth

The shear stress of a cohesive sediment bed  $\tau_c$  usually increases with depth and volumetric weight. Hence, for a given fixed shear stress  $\tau_0$ , when the shear stress at a certain depth  $\tau_c$  equals  $\tau_0$ , erosion will eventually stop [1]. Only when dynamic actions strengthen again and exceed the shear stress of that sediment layer  $\tau_c$ , sediments in deeper layers will start to become suspended. This is a characteristic of layered erosion. There are various published studies on the initiation of sediment motions or sediment erosion, but these focused on motion initiation or erosion. Additionally, only a few published reports exist on the profiles of sediment motion initiation. Zhu et al [2], suggested that current research on initiation erosion mostly focused on the bed surface of the sediment, but there were relatively few studies on group erosion. Bale et al [3], used a ring-shaped flume in the field to measure the critical sediment erosion at different depths,



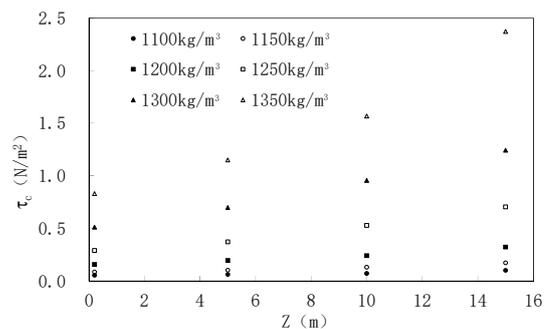
**Fig. 3** Relationships between the critical initiation shear stresses at different water depths and volumetric weights

#### 4.3 Relationships of the critical initiation shear stress with the Bingham yield stress

The Bingham yield stress of the fluid mud from the Xiaolangdi reservoir with a mean particle diameter of

but they presented only discrete data instead of formulae. This makes the application of these results in mathematical model calculations difficult. Therefore, based on the experimental data of this study, the relationship between  $\tau_c$  and depth  $z$ , that is, the profile of the critical initiation shear stress, is thus established. This can provide a vertical variable  $\tau_c$  for mathematical models and thus enhance the goodness-of-fit of the simulation results against actual situations.

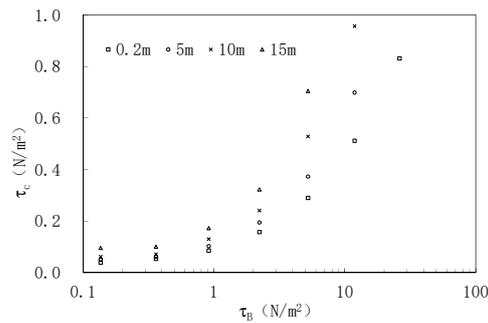
Figure 3 shows the variations in the critical initiation shear stresses  $\tau_c$  of reservoir fluid mud at different water depths as a function of volumetric weight  $\gamma_m$ , while Figure 4 shows the variations in the critical initiation shear stresses  $\tau_c$  at different volumetric weights as a function of water depth  $z$ . It is found that the critical initiation shear stress  $\tau_c$  of the reservoir's fluid mud with a mean particle size of 0.006 mm increases exponentially with the volumetric weight  $\gamma_m$  and water depth of the fluid mud.



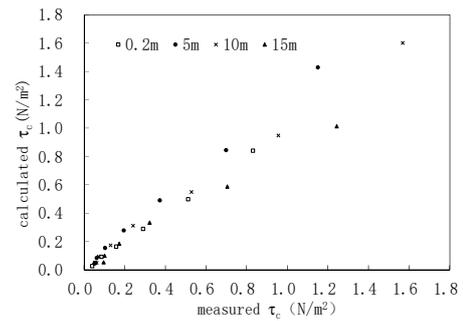
**Fig. 4** Relationships between the critical initiation shear stresses at different volumetric weights and water depths

0.006 mm varies as a function of the sediment concentration and the mean particle diameter, as described below [4]:

$$\tau_B = 1.42 \times 10^{-2} \frac{S_v^5}{d_{50}^3} \quad (1)$$



**Fig. 5** Relationship between the critical initiation shear stresses at different water depths and the Bingham yield stress depths



**Fig. 6** Experimental and calculated values of the critical shear stress of fluid mud depths

The relationship between the critical initiation shear stress  $\tau_c$  and the Bingham yield stress  $\tau_B$  under the action of water flows is as shown in Figure 5. It is discovered that the critical initiation shear stress  $\tau_c$  of fluid mud with a mean particle diameter of 0.006 mm is significantly lower than the Bingham yield stress  $\tau_B$ , and the two variables are associated based on a power-function relationship. This is because of the following reasons. (1) The values of  $\tau_B$  are not the true yield stresses of the sediments  $\tau_y$ , which are remarkably smaller than  $\tau_B$  and cannot be determined easily. (2) The sediment heterogeneity influences the experiments. (3) The value of  $\tau_c$  is a time-averaged value so it differs from the instantaneous maximum by a certain amount.

#### 4.4 Expression of the critical initiation of shear stress

Based on the experimental conditions of this study, multiple regression of the critical initiation shear stress of fluid mud  $\tau_c$  on water depth  $Z$  and volumetric weight  $\gamma_m$  can be expressed as follows :

$$\tau_c = 1.72E - 46 \times Z^{0.16} \times \gamma_m^{13.93} \quad (2)$$

The experimental and calculated critical initiation shear stresses of the reservoir fluid mud  $\tau_c$  are listed in Figure 6. It is noted that Equation (2) can calculate the critical initiation shear stresses of reservoir fluid mud at different combinations of water depths and volumetric weights.

## 5 Conclusions

Based on motion initiation experiments of the reservoir fluid, this study investigated critical initiation shear-stress-relevant parameters. The following conclusions are drawn:

- (1) The critical initiation shear stress of the reservoir fluid mud increased exponentially with the volumetric weight of the fluid mud and the water depth
- (2) The critical initiation shear stress of the reservoir fluid mud was significantly smaller than the Bingham yield stress. The two exhibited a power-function relationship
- (3) The re-initiation of the reservoir fluid mud motions significantly impacted the sediment diversion efficiency of the reservoir during the water storage period. Owing to the limitations of the experimental conditions, it was very difficult to simulate fluid mud motions. Hence, simulation studies on their patterns require additional improvements.

## Acknowledgment

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