# Effects of mud slurry on flow resistance of cohesionless coarse particles

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## ARTICLE INFO

## ABSTRACT

Laboratory experiments were performed to investigate the effect of mud slurry on the flow resistance of cohesionless particles in debris flow. For one thing, natural angles of repose were measured for the gravel materials resting in air, in water, and in mud slurry separately. For another, rheological tests were taken using a vane rheometer to measure the torque-time response of sand particles within mud slurries of varying solid concentrations both at low and high rotational speeds. The stable torque obtained at the low rotational rate, which represents flow resistance primarily caused by particle contact friction, was nondimensionalized to compare the internal friction coefficient in each case. Furthermore, flow resistance of sand particles within one of the mud slurries was measured over a wide range of rotational speeds to compare with that in the dry system. It was found that the mud slurry has no significant effects on the frictional coefficient of cohesionless coarse particles. However, the mud slurry tends to decrease flow resistance of the particles, with the effect being more significant at higher rotational speeds or for more concentrated slurries. This derives from excess pore fluid pressure, which is easier to maintain at higher shear rates or within more cohesive slurries.

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## 1. Introduction

Debris flow is a natural phenomenon with the flow behavior between those of hyper-concentration flow and landslide. The solid fraction in debris flow has a wide size distribution varying from clay particles to boulders. It is not uncommon to regard debris flow as pseudo-homogeneous and describe its behavior with rheological models. This method encounters difficulties in explaining some complex phenomena with debris flow, such as particle size segregation [1]. As a result, two-phase fluid models have been increasingly employed in dynamic simulation of debris flow [2–4]. In such models, the fluid phase is comprised of water and fine particles homogeneously dispersed in water, while coarser particles constitute the solid phase [5]. Both Bingham model and Herschel-Bulkley model are widely utilized to characterize rheological properties of the fluid phase [6]. A number of studies have focused on this issue and reveal that the rheological parameters are influenced by such factors as particle size distribution, solid volume concentration, and mineral composition [7–8]. Particles that comprise the solid phase of debris flow are cohesionless. Their flow characteristics are similar to that of granular flow, in which field paramount progress has been achieved in recent years, including the rheological expression in flow resistance of monodisperse particles [9–10] and particle size segregation in polydisperse granular avalanches

[11–12]. For debris flow, clay particles are included in the fluid phase. Flume experiments suggest that the existence of a certain fraction of clay minerals contributes to maintaining excess pore water pressure in debris flow and thus enhances its mobility [13–14]. Consequently, influences exerted by the fluid phase on flow resistance of the solid phase should be taken into account.

Some researchers have conducted studies regarding effects of interstitial fluid on granular flow. Experiments on granular matter in Newtonian fluids in a rotating drum reveal that velocities of the particles decrease with increasing fluid viscosity, while the angle of repose with a liquid interstitial fluid is larger than that for the dry system [15–16]. Using a pressure-imposed shear cell, Boyer et al. [17] study the rheology of cohesionless particles dispersed in a fluid with the same density as the particle and establish relationships of the frictional coefficient and the solid volume concentration with a dimensionless viscous number. Fluids employed in these studies were Newtonian. In contrast, the fluid phase in debris flow is mud slurry which exhibits yield stress and probably produce different impacts on flow behaviors of granular matter. In this respect, experiments conducted by Ancey [18] provide some valuable results. Making use of vane rheometry, Ancey [18] investigates the bulk behavior of concentrated suspensions of coarse and fine (colloidal) particles in water and finds that the bulk behavior varies both with the concentration of fine particles and the shear velocity.

The present research mainly refers to the method used by Ancey [18] and studies effects of mud slurry on the flow resistance of granular matter. Instead of paying attention to flow behaviors of the suspensions, we focus on comparing the flow resistance of cohesionless particles in mud
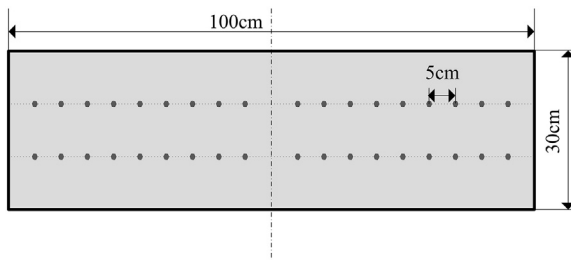
**Fig. 1.** Measurement positions with the thread method.

slurries of different concentrations. In this paper, Section 2 introduces experimental materials and procedure, while Section 3 analyzes the results following which is the conclusion part.

## 2. Experimental procedures

### 2.1. Experiment on the angle of repose

For cohesionless particles, the angle of internal friction approximately equals the natural angle of repose [19]. As a consequence, effects of mud slurry on the internal frictional angle of granular matter could be preliminarily examined by comparing the natural angles of repose measured in air, in water, and in the mud slurry, respectively.

#### 2.1.1. Materials

To prepare the slurry, we used the fine fraction (<1 mm) in the debris flow sediment sampled from Jiangjia Gully, Yunnan Province, China. According to the measurement by a Mastersizer 2000 laser particle size analyzer, the median particle size of the material is 0.022 mm, with clay minerals (<0.005 mm) accounting for 24.8%. The particle density is 2752 kg/m³. Dongchuan Debris Flow Observation and Research Station, Chinese Academy of Sciences has carried out observation at Jiangjia Gully for >50 years. Measurement data show that in viscous debris flows, the densities of which are >2000 kg/m³ [20], the solid volume concentration in slurry suspensions comprised of fine particles (<1 mm) and water changes from 0.248 to 0.443, with an average of 0.349. Based on the average concentration, we prepared the mud slurry with a bulk density of 1611 kg/m³. All the fine particles could maintain suspended for a long time in the slurry. Gravels of 10–20 mm in size were used as coarse particles in this experiment. The particle density is approximately 2750 kg/m³. These gravels could settle immediately in the slurry.

#### 2.1.2. Experimental setup and procedure

The experiment was performed in a horizontal glass tank, which is 100 cm long, 30 cm wide and 70 cm deep. Considering the nontransparent feature of the slurry, we used the following procedure to get the natural repose angle of gravels in the slurry: (1) prepare the slurry and pour it into the tank, then mix the slurry thoroughly by hand; (2) pour the gravels into the slurry gradually along the central line of the tank surface (Fig. 1), thus a sediment deposit is formed; (3) use a fine thread (0.25 mm in diameter) tied to a steel bead (20 mm in diameter) on one end to measure the distance between the deposit surface and the tank surface at specific positions, which are 1/3 or 2/3 of the width to the long side wall of the tank with an interval of 5 cm, as illustrated in Fig. 1; (4) plot the measurement data versus the distance between the measurement position and the short side wall of the tank, and then fit data points with a straight line, thus achieving the angle of repose. When measuring the angles of repose in air and in water, the same procedure was followed except step (1). For convenience, this method for determining the angle of repose is called thread method.

To check accuracy with the thread method, the triangle method was also employed when determining the angles of repose in air and in water. In this method, a triangle was depicted on the wall following the deposit surface [19], as shown in Fig. 2. Therefore, for coarse particles depositing in air or in water, we got four angle values with each method in one test. For these cases, the test was repeated once. For gravels depositing in the slurry, there were no repeated tests. Nevertheless, in this case additional measurements were performed at positions that were 1/6, 1/2, or 5/6 of the width to the long side wall of the tank, thus generating ten angle values in total.

### 2.2. Rheological experiment

#### 2.2.1. Materials

Mud slurries in the rheological experiment were prepared with finer particles (<0.075 mm in diameter) than that used in the experiment on the natural angle of repose. These materials were also collected from Jiangjia Gully. The particle density is 2752 kg/m³ and the median particle size is 9.5 μm. Six different slurries were made with the solid volume concentration $C_{vf}$ ranging from 0.048 to 0.292, as listed in Table 1. Rheological tests were performed on these slurries with the roughened concentric cylinder system of an Anton Paar Physica MCR301 rheometer (radius of the rotor: 15.22 mm, length of the rotor: 45.60 mm, radius of the cup: 21.00 mm, roughness: 0.5 mm). The curve of shear stress versus shear strain was used to derive yield stress [21]. Repeated tests



**Fig. 2.** Sketch map of the triangle method.