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FLOW PATTERNS FOR MUDDY MATERIAL IN A ROTATING DRUM

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ABSTRACT

We perform rheological measurements in a rotating drum. As a starting point for using formula to calibrate rheological measurements, we first identify the possible flow phenomenon in the drum. The experiments were conducted in a drum with 0.5 m inner radius and 0.2 m width. The material used is a Kaolin/water mixture. The rotating speeds varied from 0 rpm to 40 rpm. The sample amount used in experiments must be large enough to assure that the flow length is much larger than its height. The three flow patterns discovered are Sliding, Swinging, and Circling. Among the three basic categories, there are other variations in each category. Some ofthe variations are unsteady patterns. We delineate the occurrence of the observed motion patterns in a diagram asa function of rotation speed and kaolin concentration.

Key words: *kaolin mixed with water, rotating viscometer*

INTRODUCTION

Taiwan is an island with fragile geology and located in the subtropical area. Frequent abundant and intensive rainfall usually induces massive soil erosion, mudflows and landslides. These flows have velocities typically in the order 10m/s and usually appear in the shape of long waves. Long travel distance up to 5 to 10Km is usual and devastating damage can be induced along the path. In order to estimate the disaster caused by mudflows, the rheological properties of such flows must be understood. However, before we can actually use experimental data to calibrate any formulae, it is essential to understand if the flow conditions in a rotating drum are suitable for rheological measurements and to develop corresponding theories. This paper therefore concentrates on describing the phenomenon that observed in the experiments. It can be seen that, many of the phenomena are actually not expected from the theoretical point of view. Even the usual assumed "steady state" is not always true.

Often rheological experiments are conducted in a vertical rotating drum similar to what is shown in Fig. 2.

Henein *et alii* (1983) has shown that there are six different patterns of motion: Slipping, Slumping, Rolling, Cascading, Cataracting, and Centrifuging (Fig. 1). They used granular material of small sizes.

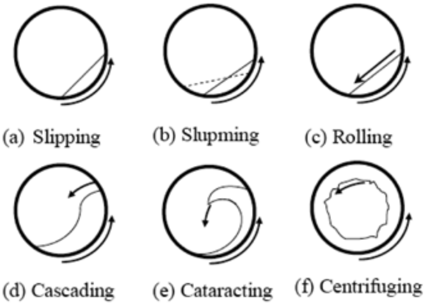

Fig 1 - The possible motion patterns of the mud and sand granules in the upright rotating sink by H.Henein (1983)

In our experiments, we focus on muddy material and similar but different flow patterns are found.

There are other experiments using slurries like material to perform rheological experiments such as Huizinga (1996), Major (1997) and Kaitna & Rickenmann (2007 a, b). Huizinga (1996) concluded that different volume put into the rotating drum is not important and the phenomena would be the same. However, this is not what we have encountered during our experiments. As the first step, we shall point out that steady flow patterns may not always be possible and the different velocity profiles of the flows may explain the experimental data.

EXPERIMENTAL METHODS

In this study, we use the equipment from Liu & Chang (2008) as show in Fig. 2. The drum has 0.5 m inner radius, 0.2 m width and rotates clockwise. The bottom of the rim is made of iron and has strips of 0.5cm width and 0.1cm height attached to increase the bottom friction. The side walls are made of reinforced transparent glass. There are 12 rotating speed used in the experiments. 3.23rpm, 6.97rpm, 10.62rpm, 14.28rpm, 17.91rpm, 21.66rpm, 25.17rpm, 28.74rpm, 32.52rpm, 36.00rpm, 39.66rpm, and 43.37rpm (the max speed). To maintain the long wave characteristics, the testing material is filled less than 1/4 of the full drum capacity.

We use Kaolin/water mixture in this study. Different volumes ranging form 6000 ml to 15000 ml were used in our experiments. All volumes produces flow characteristics corresponding to a long wave and yet thick enough for meaningful observation. In this

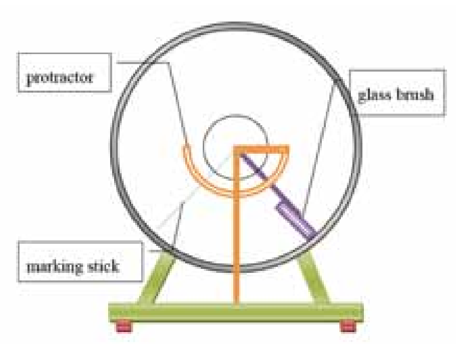

Fig. 2a - Front view of the vertical rotating viscometer according to Liu & Chang (2008)

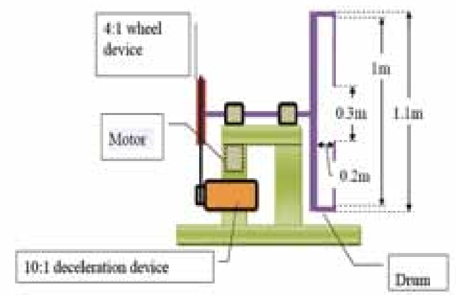

Fig. 2b - Front view of the vertical rotating viscometer according to Liu & Chang (2008)

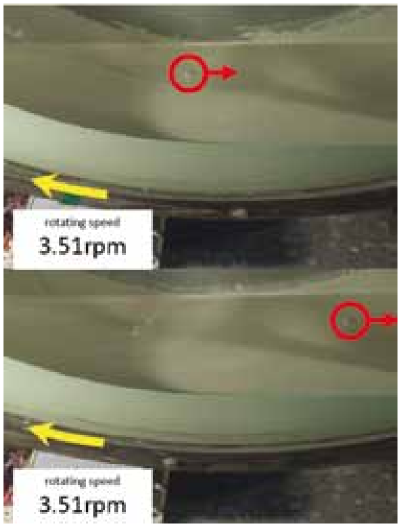

Fig. 3 - Flow for a mixture with Kaolin concentration 25.38% and 3.51rpm rotating speed. The surface velocity is counter-clockwise. This can be seen from the movement of the bubbles on the free surface. Two consecutive location of the same bubble is marked in the photos

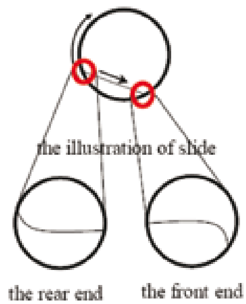

Fig 4 - Sliding motion: shape of the rear and front end of the moving mass paper we shall describe the observations made for a total sample volume 9000 ml. All patterns reported in this paper were also observed for other volumes but at different rotation speeds and concentrations. As the concentration of mixture reaches 47.96% for total volume 9000 ml, all the materials would simply adhere with the drum wall. Therefore, 47.96% was the highest concentration in our study. 9 different concentrations were used in our experiments, i.e. 25.38%, 31.47%, 37.19%, 38.76%, 41.30%, 43.63%, 45.27%, 47.13%, and 47.96%.

EXPERIMENTAL RESULTS

We first use the result form Kaolin concentration of 25.38% and rotating speed of 3.57rpm as an example to describe our experimental procedure. After mixing of /water mixture, we put the sample in the drum and start the drum with the highest rotating speed. Then we reduce the rotating speed gradually to desired speed and maintain that speed for 5~10 minutes until steady state is reached. All the measuring can be done after that.

In the experiment with a Kaolin concentration of 25.38% and 3.51rpm rotating speed, it was found that the free surface moved counter-clockwise downward. This is confirmed by observing small bubbles on the free surface which moves counter-clockwise as shown in Fig. 3. Since mixture must move clockwise in the bottom so there must be a boundary with zero velocity. When the motion reaches a steady state, the bottom material is brought up by the rotation of drum and brought down by gravity. In this case, the mixture forms a steady pile with a front and a tail as shown in Fig. 4. The measurement is done with the central part of flow without the front and the tail influence. At this particular case, the front and the tail span 80° apart respect to the center of drum. The maximum thickness of the material was 10.9cm and located approximate at the mid point of the whole pile

After observing different phenomena in the drum, we can first divide these phenomena into three basic categories: Sliding, Swinging, and Circling, the basic motion patterns which are illustrated in the Fig. 5. Within each category, there are further variations according to the free surface conditions..

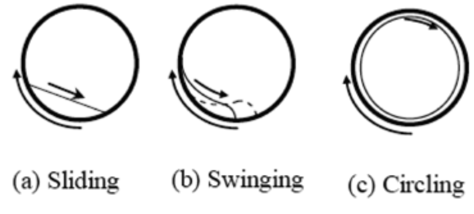

Fig 5 - The 3 basic flow patterns observed during the experiments

SLIDING

This flow pattern is just the standard case discussed before. Mixture contains two flow regions with lower region flow upward by bottom stress and upper region flow downward by gravity. The front position remains at the same location for all time. The maximum thickness of the mixture varies from 6.7cm to 10.9cm for different concentrations and different rotating speeds. This flow pattern is similar to the rolling phenomenon among the six motion patterns observed by Henein (1983). We defined the phenomena with stable fronts as Sliding. In Fig. 6, we mark all runs with this pattern in the rotating speed vs. concentration graph.

The pattern does not exist for high rotating speed or very high concentration. For high rotating speed, the bottom stress is high enough to break the balance. For very high concentration, the yield stress and viscosity preventssignificant flow motion.

SWINGING

As the concentration increases, the viscosity increases, so the bottom stress becomes larger. It is not so easy for gravity to balance the stress, so the whole pile of mixture will rise to even higher position (the rear end in Fig. 4) before gravity can be effective. Since the total volume of sample is fixed, the front is pulled

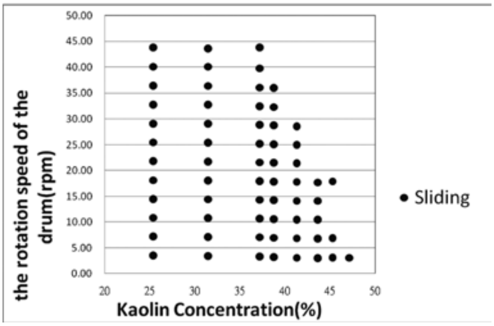

Fig 6 - Domain for stable Sliding patterns observed

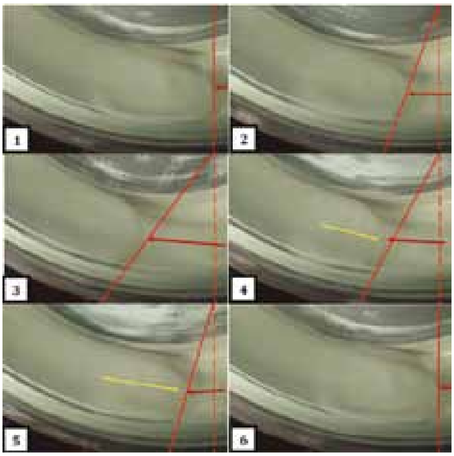

Fig 7 - The red line indicates the front of the pile and dashed red line is the original front location. Photo 1 to 6 are the consecutive photos at time interval 0.33sec. This sequence demonstrates a complete period of the front (Kaolin concentration 45.27%. Rotating speed 28.57rpm)

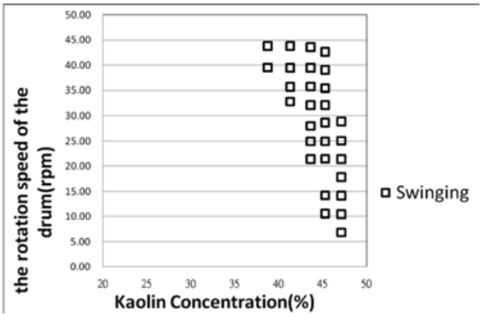

Fig 8 - Domain for periodic Swinging patterns observed

higher also. As a result, the front position will move upward and then drop downward to form a periodical motion. The motion patterns were illustrated in Fig. 7 This is not a steady state but a quasi steady state. This type of phenomena is similar to the Swinging phenomenon among the six motion patterns by Henein (1983). Therefore, it was named Swinging. All runs with Swining pattern are marked in Fig. 8. As can be seen, this pattern only occurs for high concentration and high rotating speed which can produce relative large bottom stress..

CIRCLING

When the concentration of the fluid is really high, all mixture actually is distributed along the wall. There is no "flow" phenomenon. As the rotating speed increases, the thickness of the mixture along the wall

Fig 9 - The even distribution of the fluid in the phenomena of Circling (47.13% concentration; 32.68rpm)

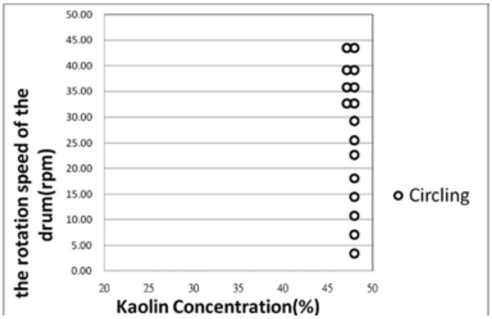

Fig 10 - Domain for Circling patterns observed

becomes more uniform. After the speed increased to 22.67rpm, the fluid distributed evenly at the entire bottom as shown in Fig. 9. This phenomenon was similar to the Circling phenomenon among the six motion patterns by Henein (1983). So it is named Circling. All cases with this pattern is marked in Fig. 10

SPECIAL SUB-PATTERNS

Besides the three basic categories, there are other variations in each category. Some variations are steady, we refer them as sub-patterns. But there are also unsteady patterns.

SLIDING SUB-PATTERN 1

Sliding means the whole pile remains at the same location with bottom layer going upward and top layer going downward. However, for high concentration and low rotating speed, there are cases where the steady pile looked the same as in other Sliding case, but with some small amplitude wave on the free surface travelling UPWARD! Placing a very light float on the free surface reveals the fact that the velocity of the free surface is travelling in the same direction as the bottom, i.e. upward (Fig. 11). However, this free surface velocity is much less than the bottom velocity and can be considered as stationary. This means there

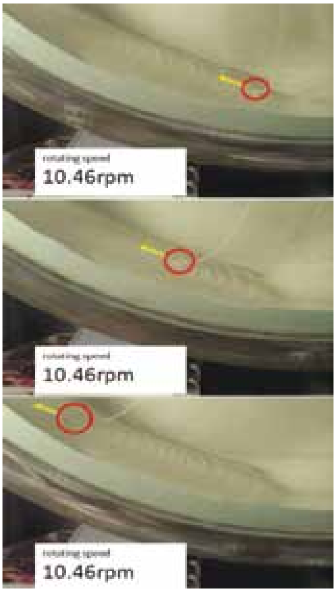

Fig. 11 - Sliding Sub-pattern 1 (Kaolin concentration 43.62%, 10.46rpm rotating speed). These three photos are consecutive photos in time interval 1sec. The float (marked with red circle) was observed to travel upward with small velocity

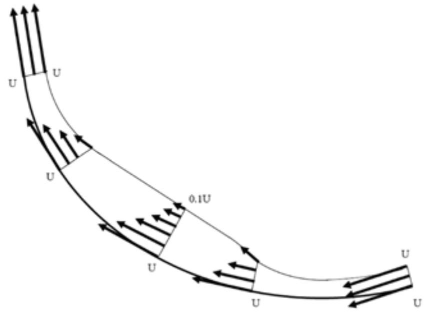

Fig. 12 - The schematic velocity profile for Sliding Sub-pattern 1. The flow rate through every section is the same

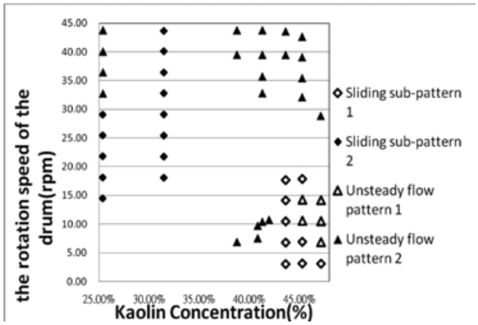

Fig 13 - Domains for Sliding Sub-pattern 1 & 2 and Unsteady flow pattern 1 & 2

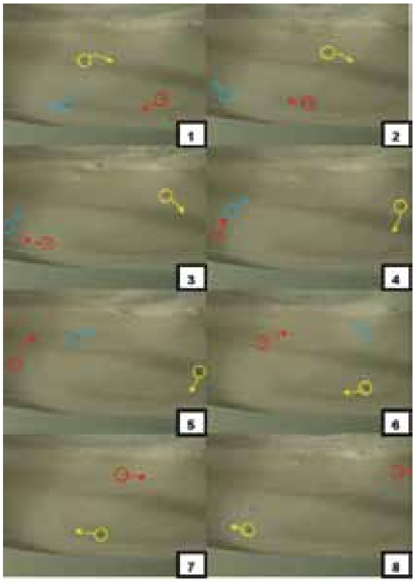

Fig. 14 - Sliding Sub-pattern 2: Photos are consecutive pictures at time interval is 0.36sec (Kaolin concentration 25.38% and 29.06rpm rotating speed). Different colours indicate motion for different bubbles. It can be seen that bubbles are moving in circles on free surface

is no reverse velocity through out the depth. Hence this Sliding phenomenon has only one layer and the whole pile is moving upward. Detailed observation even shows that the small wave is produced due to piling effect at the front.

The flow depth for these phenomenon ranges from 4.1 cm to 6 cm and varies with concentration and rotating speed. All runs of this type appear on the lower right corner of Fig. 13. These points are close to the boundary between Sliding and Circling.

This is a steady case and can last as long as one hour, which is the maximum observation time for all our runs.After testing the velocity through depth, we can conclude that this is a one layer structure with whole layer travelling clockwise. Since the longitudinal profile remains unchanged so the vertical integrated flux rate must be the same through longitudinal direction. A schematic graph of the velocity profile is drawn in Fig. 12.

SLIDING SUB-PATTERN 2

There are runs with two dimensional flow patterns. These runs are usually for low concentration and high rotating speed. The typical 2-D pattern can be observedthrough the bobbles on the free surface (Fig. 14).

Fig 15 - *Unsteady flow pattern 2: Surface waves affect the position of the front. Kaolin concentration was 41.30%, and the rotating speed was 39.52rpm*

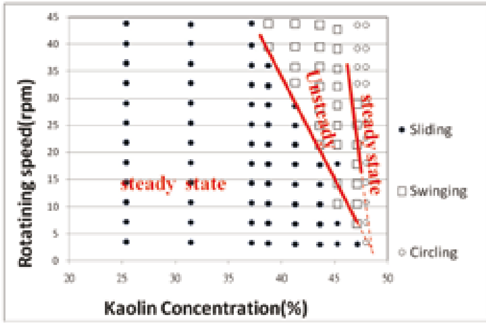

Fig 16 - *The boundary lines separating Sliding, Swinging and Circling. Results are for Kaolin/water mixture and total volume of 9000ml*

The whole pile moves just as the standard case. Top layer moves downward with a steady front. However these bubbles on free surface have 2-D circling trajectories

The bubbles were generated at the tail. When mixture was brought up to the tail region, it would fall and merge to the whole pile. But the falling generates bubbles, and bubbles show this 2-D Circling motion. It is possible that the falling is affected by sidewall and thus creates this 2-D motion. All runs with this feature are marked in Fig. 13.

UNSTEADY FLOW PATTERN 1 -INTERMITTENT

For runs with condition close to the Sliding subpattern 1, it is possible to have unsteady motion. It looked like when the free surface has a small velocity in the same direction of the bottom, mass transported with bottom can be blocked. When blocked mass accumulated to a threshold, the top layer is forced to move faster. But once the blocking situation is released, it returns to sub-pattern 1. Points with this feature are marked in Fig. 13 with $^{\Delta}$..

UNSTEADY FLOW PATTERN 2 - WAVES

In our experiment, when the concentration is high, it is possible to have lobe of mixture been brought up and fall as a whole. This falling is typically 2-D and creates waves on the free surface. As waves travel to the front, these waves can affect the distribution of the front. The influence depends on the amount of the lobe that falls. Typical surface disturbance is shown in Fig. 15. All runs with this feature are marked in Fig. 13 with ▲

CONCLUSION

The motion of fluid in the rotating viscometer would vary according to different rotating speeds and Kaolin concentrations. We divided the observed phenomena into three categories, namely Sliding, Swinging, and Circling, and we further divided them into sub-categories according to their different motion characteristics. Sliding can have two more sub-patterns.

Combing the results for the three major patterns in one graph allows us to delineate the boundaries of the domains (in terms of rotation speed and concentration) in which these patterns appear. Red lines in Fig. 16 are the two boundaries separating the three major patterns.

The two boundaries lines will vary for different total volumes and of course for different material such as Kaolin/water or Bentonite/water mixture. Experiments reported in Huizinga (1996) may all fall within our sliding case.

The important discovery is that the Sliding subpattern 1 is a one layer structure other than commonly believed two opposite moving layers. Also, the discovery of unsteady pattern and 2d pattern (Sliding sub-pattern 2) indicate that assuming a steady 1-D flow may not always be true

. As the next step, we will try to complete a three dimensional graph with concentration, rotation speed and total volume as three parametric axes. This can give us a more complete understanding of the variation. With the full understanding of the variation of phenomenon, then accurate theoretical treatment for motion in rotating drum is possible.

ACKNOWLEDGEMENTS

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