15th Australasian Fluid Mechanics Conference
The University of Sydney, Sydney, Australia
13-17 December 2004

An Experimental Study of Sudden Release of Bentonite Suspensions down an Inclined Chute

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Abstract

Bentonite suspensions, used in the construction industry, are non-Newtonian fluids with a thixotropic behaviour. Sudden releases of bentonite suspensions were systematically investigated down a sloping chute, to quantify the effects of bentonite concentrations and initial rest period on flow motion. Experiments observations highlighted four types of flows, that differ substantially from Newtonian fluid motion. Quantitative informations were documented in terms of the fluid thickness, wave front position and wave front curvature during motion and after stoppage. It is believed that the present study is the first systematic study of its kind in a large-size facility.

Introduction

Bentonite suspensions are commonly used in the construction industry for drilling and tunnelling. They are non-Newtonian fluids with a thixotropic behaviour. Such a behaviour is also found in liquid concrete, pasty cements, clay-water mixtures used by the beauty industry for skin treatment, and some forms of mud flows and debris flows [2,6,7]. Thixotropy is the characteristic of a fluid to form a gelled structure over time when it is not sheared and to liquefy when agitated. The apparent viscosity of the fluid is a function of both shear intensity and current state(s) of structure of the material, sometimes called degree(s) of jamming of the fluid [3].

In this paper, an experimental study of sudden releases of bentonite suspensions was conducted down a sloping channel. The effect of bentonite mass concentrations and initial rest periods were systematically conducted. The results provide an unique databank of thixotropic fluid motion in highly unsteady flow conditions.

Bibliography

Although non-Newtonian fluid mechanics has been studied for sometimes [2,4], thixotropy was understood relatively recently [6]. Up to date, experimental studies were often limited to very simplistic conditions to study primarily the fluid rheology [5,7]. Sudden releases of thixotropic fluids have not been studied despite the relevance to industry: e.g., L-ring concrete tests for self-compacting concrete.

Experimental Setup

New experiments were performed in a 2 m long, 0.34 m wide, tilting flume (Fig.1). The sidewalls were made of polycarbonate panels, while the invert was covered with grade 150 sand paper to minimise slippage. A removable gate was installed and tilted 15º with the direction normal to the channel invert. All experiments were conducted with a fixed bed $\theta_b = 15°$ for which the sluice gate was vertical.

The channel slope was measured with an electronic inclinometer Digital Protactor Pro360 with an accuracy of 0.1°. For the preparation of the suspensions, bentonite and water were weighted with a balance Sartorius LP3200D with an accuracy of less than 0.01 g. During experiments, the mass of bentonite suspension was weighted with a balance Metler PM16 with an error less than 1 g. The rheological properties of suspensions were measured with a Rheometer Bohlin Instruments C-VOR 200 NF, equipped with two rough circular disk (∅ = 40 mm). Flow visualisations were performed with four digital video-cameras with high-shutter speed : Canon MV500i (25 fr/s, shutter: up to 1/8,000 s), Sony CDR-TRV950E 3CCD (25 fr/s, shutter: up to 1/10,000 s), Olympus Camedia C700 (15 fr/s, shutter: up to 1/1,000 s) and a CCD camera (25 fr/s) connected to a computer system. Unsteady free-surface elevations were measured using the CCD camera at the intersection of a series of laser beams (He/Ne 10mW) illuminating the free-surface at low incidence. The data were analysed using a Mourier projection method. Further details on the experiments were given by Chanson et al. [1].

Fluid preparation

Great care was taken to prepare systematically and consistently the bentonite suspension using the procedure described by Huynh et al. [5]. Solid mass concentrations between 10 and 20% were used. The bentonite solutions were prepared with distilled water and industrial grade bentonite (Impersol powder, Société Française des Bentonites et Dérivés, France) with no chemical additives. The bentonite-water suspensions were first agitated continuously for about 3 h to ensure complete homogenisation. The suspensions were then left to rest for at least 48 h to allow hydration and dispersion of bentonite particles.

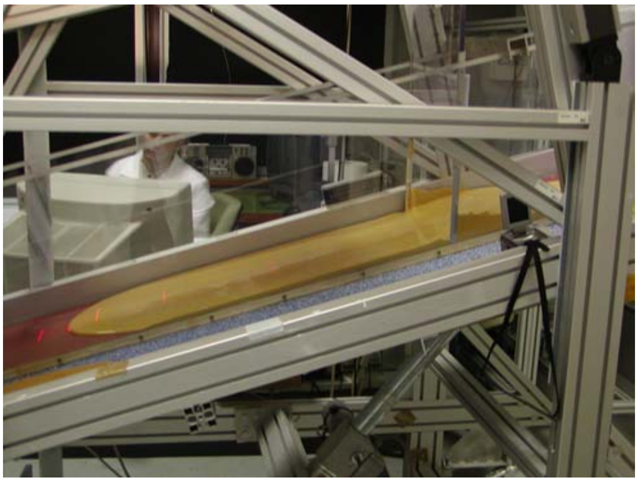
Herein the mass concentration C_m is defined as the ratio of mass of bentonite to mass of bentonite plus water. The density ρ of bentonite suspension equals :

$$\rho = \frac{\rho_w * \rho_b}{C_m * \rho_w + (1 - C_m) * \rho_b} \qquad (1)$$

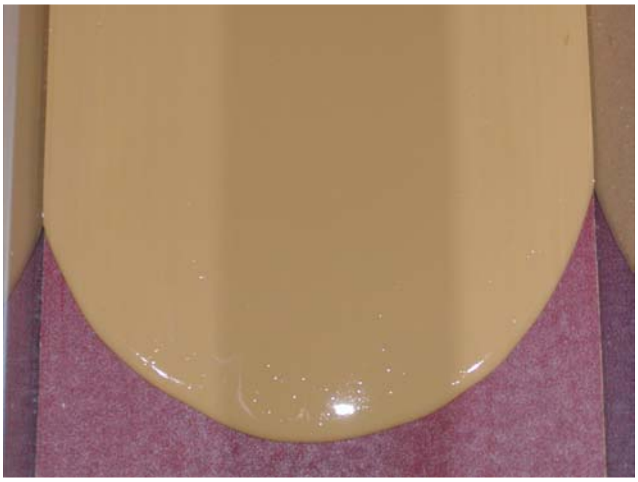
where ρ_w is the water density and ρ_b is the bentonite density (2600 kg/m^3).

Basic properties of bentonite suspensions were measured with the rheometer equipped with rough circular disks separated by a 1 mm gap. The tests were performed under controlled stress for relatively short durations at constant temperature (25 Celsius). For each test, a small sample of well-stirred liquid was pre-sheared at constant a shear rate of 500 s^{-1} for 20 s. It was then rested for a known period T_o before being subjected to a controlled stress loading and unloading of 1 minute each.

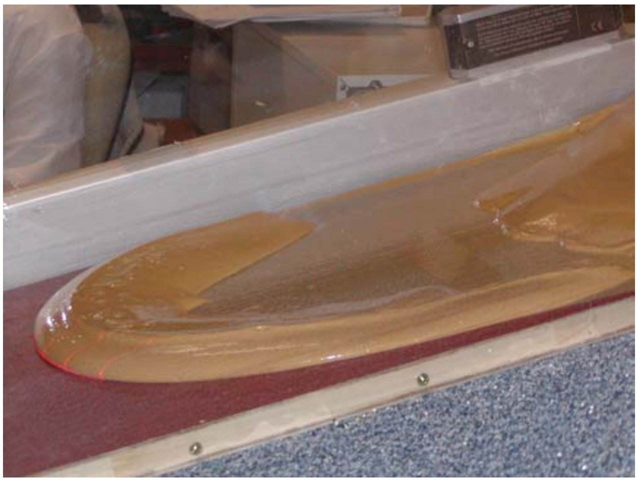
Results provided some information on the apparent yield stress of the fluid τ_c and the effective viscosity μ as functions of bentonite suspension mass concentrations and rest times. The apparent yield stress and viscosity were estimated during the unloading phase, to be consistent with the inclined plate experiments. Experimental results showed an increase in apparent yield stress with increasing rest time for a given mass concentration, as well as a marked increase in apparent yield stress with mass concentration for a constant rest period. Viscosity data indicated little effect of mass concentration and rest period. In average over all tests, the apparent viscosity was 0.34 Pa.s for $1 < T_o < 900$ s and $0.10 < C_m < 0.17$.



(A) Flow type II, Test 03, C_m = 0.15, rest period: T_o = 60 s



(B) Flow type II, Test 05, C_m = 0.15, rest period: T_o = 60 s - View in elevation of the leading edge



(C) Flow type III, Test 08, C_m = 0.15, rest period: T_o = 2400 s - Sideview of the head packet

Fig. 1 - Photographs of experimental tests (taken after stoppage).

Preparation of experiments

Prior to each test, the bentonite suspension was stirred for about 1 hour to ensure that the fluid was completely de-structured. The suspension was poured upstream of the closed sluice gate where it formed a quasi-two-dimensional, triangular reservoir with a horizontal free-surface. The suspension was rested for a given period of time T_o before the gate was suddenly opened. The gate removal was rapid (less than 0.05 s). All measurements were conducted in ambient conditions (i.e. 20 Celsius).

Basic Flow Patterns

Experiments were performed with mass concentrations of 0.10, 0.13, 0.15, 0.17 and 0.20, rest times between 20 s and 17 h, and initial mass of fluid between 1.6 and 4.1 kg. For that range, the results demonstrated four basic fluid flow patterns. Some are illustrated in Figure 1.

For small bentonite mass concentrations ($C_m \le 0.15$) and short relaxation times ($T_o \le 30$ s), the fluid flowed rapidly down the constant slope all along the plate length, and it spilled into the overflow container (Flow Type I). During the initial instants immediately following gate opening, inertial effects were dominant and the flow was subjected to a very-rapid acceleration (see below).

For intermediate concentrations and rest periods, the suspension flowed rapidly initially (as described above), decelerated relatively suddenly, continued to flow slowly for sometimes and later the flow stopped, often before the plate downstream end (Flow Type II). Observations suggested distinct flow periods. Immediately after gate opening, the fluid was rapidly accelerated and quasi-two-dimensional. Then the suspension continued to flow rapidly although sidewall effects started to develop with a slower front propagation at and next to the walls. Later the fluid decelerated relatively rapidly, and this was followed by a significant period of time during which the suspension continued to flow slowly before stopping ultimately. During and after fluid deceleration, careful video analysis suggests that the front propagation was subjected to some form of perturbations. That is, the wave front (on centreline) seemed to accelerate and decelerate with periods of about 0.1 to 0.25 s.

For relatively large mass concentrations and rest periods, the mass of fluid stretched down the slope, until the head separated from the tail (Flow Type III). After separation, a thin film of suspension connected the head and tail volumes which could eventually break for long travelling distance of the head. The head had a crescent shape (Fig. 1C). For long rest periods (i.e. several hours), several successive packets were sometimes observed (Flow Type IIIb).

The last flow pattern (Type IV) corresponded to an absence of flow. That is, for very large bentonite concentrations and the longest rest times, the fluid may not flow at all after gate opening, even after waiting 30 to 60 minutes.

Transition between flow regimes

The characteristic conditions for the transition between flow regimes were functions of the mass concentration of bentonite suspension, rest time and initial mass of fluid M. A summary of the observations is shown in Figure 2 for a fixed mass M. Basically the type of flow regime changed from no flow (Type IV) to a rapid flow (Type I) with increasing mass M, decreasing mass concentration C_m and decreasing rest period T_o. Figure 2 illustrates the trend in terms of mass concentration and rest period for a given mass of fluid (and constant plate slope).

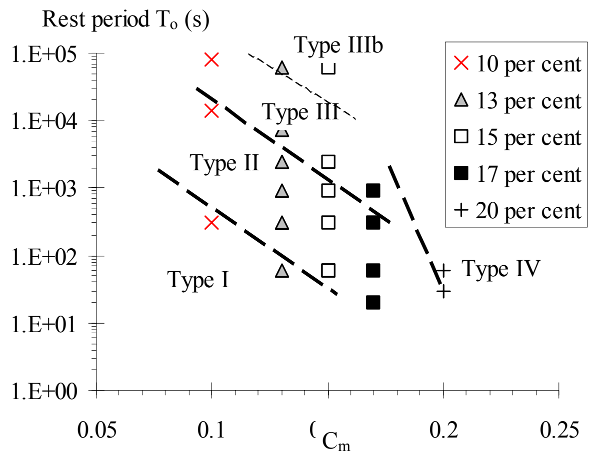
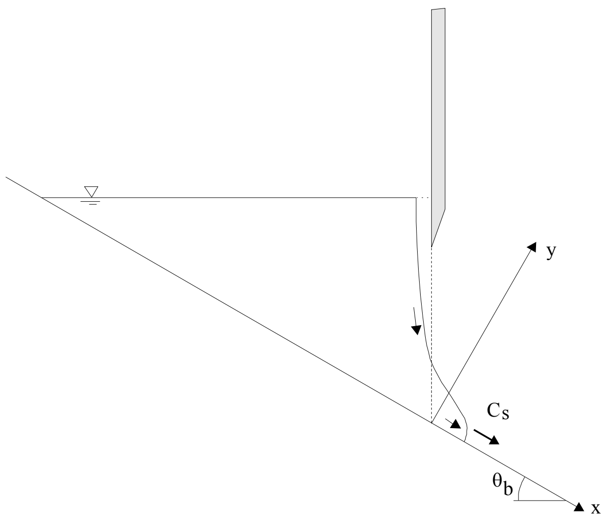
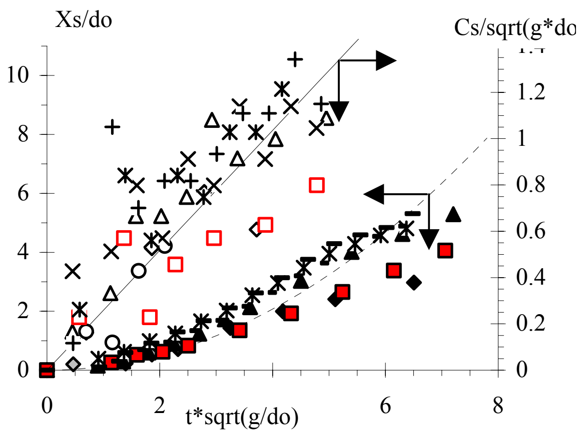


Fig. 2 - Chart of flow regimes : rest time as function of the mass concentration for a given mass of fluid (M = 3.7 kg). Comparison with experimental flow conditions.



(A) Definition sketch



(B) Experimental results

Fig. 3 - Initial jet flow : wave front propagation immediately after gate opening.

Experimental results

Initial jet flow

For Flow Types I and II (possibly some Flow Type III), the initial instants following the gate opening were characterised by a very-rapid acceleration of the fluid, somehow similar to a two-dimensional jet flow motion. Experimental data demonstrated that the flow acceleration derived solely from the gravity force component in the longitudinal direction (Fig. 3). That is, immediately after gate opening, the fluid was subjected to an acceleration component parallel to the plate of about $-g*\sin\theta_b$, where g is the gravity acceleration, and flow resistance was negligible. Within these assumptions, the equation of motion compared favourably with the data for $t*\sqrt{g/d_o} < 4.5$ to 6 (e.g. Fig. 3B). In Figure 3B, the dimensionless wave front location X_s/d_o and wave front celerity $C_s/\sqrt{g*d_o}$ are plotted as functions of the dimensionless time $t*\sqrt{g/d_o}$, where d_o is the initial reservoir height measured normal to the gate, and t is the time. Experimental observations showed further that the initial jet flow motion was quasi-two-dimensional and that it was little affected by bed friction.

Discussion

For all experiments, the maximum shock celerity was recorded at the end of the initial jet flow motion. The results were basically dependent only upon the Flow Type. The Reynolds number estimated in terms of the maximum shock celerity $(C_s)_{max}$, initial reservoir height d_o and measured fluid properties was $\rho*(C_s)_{max}*d_o/\mu = 310$, 150 and 73 for Flow Types I, II and III respectively, where μ is the effective viscosity of the destructured fluid.

The lesser maximum shock celerity observed in Flow Types II and III may indicate some incomplete destructuration of the fluid at gate opening. Note that the Reynolds number in Flow Type I was significantly high. Turbulent flows may be observed for such Reynolds numbers with large roughness, and it is conceivable that turbulent flow motion was experienced during the present study in Flow Type I.

Shock front curvature

After the initial jet flow motion, the flow became rapidly three dimensional with the development of a marked front curvature, viewed in elevation, for all investigated flow conditions. This is well illustrated in Figures 1B and 4. The results showed that the front curvature increased with time, hence the travelled distance X_s, for a given experiment (Fig. 4). Further video-observations demonstrated slower fluid motion next to the sidewalls. For all experiments, the flow curvature developed very rapidly, and it exhibited a power law profile that was best fitted by :

$$\frac{Z}{d_o} \sim \left(\frac{X}{d_o}\right)^{0.4} \qquad (2)$$

where $X = X_s - x$, Z is the transverse distance measured from the centreline and x is the longitudinal coordinate of the front (Fig. 4). Basically X = 0 and Z = 0 at the shock front on the channel centreline. Equation (2) was obtained independently of time t, initial mass M, mass concentration, rest period and flow regime. It is compared with experimental observations in Figure 4.

Since the polycarbonate panels of sidewalls were much smoother than the invert, it was probable that sidewall friction did not play a preponderant role in the very-rapid development of front curvature. Calculations showed that sidewall boundary layers were thin and could not explain the brisk development of curved profile over short distances, as observed in the present study. The front curved profile might in fact result from interactions between sidewall and bottom boundary layers. Indeed the flow was quasi-two-dimensional as long as flow resistance had little effect on the fluid motion.

Interestingly Huang and Garcia [4] presented a photograph showing a similar front curvature with kaolinite suspension mud flows, but they did not elaborate on the shock front curvature.

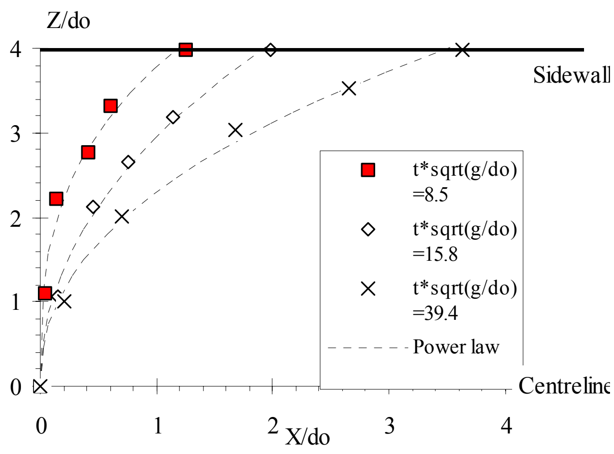


Fig. 4 - Curved profiles of the shock front, viewed in elevation : Test 23, $C_m = 0.13$, M = 3.7 kg, $T_o = 60$ s, Flow Type I.

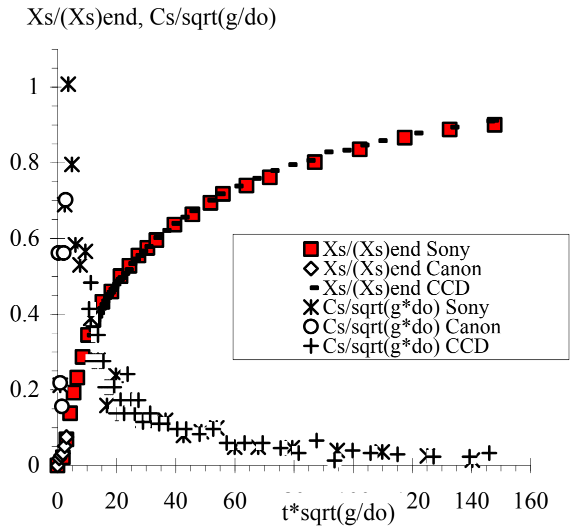


Fig. 5 - Wave front propagation on the channel centreline as function of the dimensionless time : Flow Type II. Test 6, θ_b = 15º, $C_m = 0.15$, M = 3.7 kg, rest period: 300 s.

Shock front propagation

The propagation of the wave front was investigated with video-cameras. A typical result is presented in Figure 5 for a Flow Type II, with the dimensionless wave front location $X_s/(X_s)_{end}$ and wave front celerity $C_s/\sqrt{g^*d_o}$ as functions of the dimensionless time $t^*\sqrt{g/d_o}$, where $(X_s)_{end}$ is the final location of the front after stoppage on the plate. In Figure 5, data from several cameras are presented showing good agreement between all data, independently of camera location and type.

For the Flow Type II, and possibly some Flow Types I and III, the extrapolation of present results to an infinitely long inclined plate yields a relationship between wave front location and time that is characterised by five characteristic periods before stoppage. (1) The initial instants following the gate opening are characterised by a very-rapid acceleration of the fluid: i.e., the initial jet flow motion. (2) When the wave front starts to become three-dimensional (Fig. 1B & 4), the relationship between front location and time becomes nearly linear, and the flow motion remains rapid. (3) For $t^*\sqrt{g/d_o} \sim 10$ to 20, a relatively strong flow deceleration is observed, which is seen by a sharp change in the shock celerity (e.g. Fig. 5). It is thought that the fluid motion at the wave front is characterised by a shear-dominated region next to the invert, an upper fluid layer and an interfacial zone. In the upper flow zone, the fluid is subjected to much less stress, it has time to restructure and its apparent viscosity increases significantly. After the marked flow deceleration, experimental observations suggest (4) a relatively slower flow motion, followed by (5) a very-slow flow motion. The latter is nearly a "creeping" motion, until stoppage.

Conclusions

This study is focused on the highly unsteady flow motion of a thixotropic fluid with a free-surface. The phenomenon is a shock during which the interactions between flow motion and fluid rheology are very strong, and the fluid is subjected to a continuous transition from a liquid to a solid behaviour.

Physical experiments were performed by pouring a given volume of bentonite suspension in a dam reservoir at the top of an inclined channel (15° slope). The mass of fluid was left at rest for a controlled time T_o before the gate was abruptly lifted. Systematic experiments were performed for a range of rest periods T_o during which the fluid restructured, for various solid volume fractions C_m, and initial mass of fluid M. Qualitatively, four flow types were observed. Quantitative informations were documented in terms of wave front curvature and initial jet flow motion. The results highlight the complexity of the interactions between flow motion and fluid rheology.

It is believed that the present study is the first experimental study of highly unsteady flow motion of thixotropic fluid in a large-size flume. Further works may include the effects of bed slope and inner velocity field in the shock flow. Theoretical developments outlined by Chanson et al. [1] may provide additional insights into the complex interactions between fluid motion and rheology.

Acknowledgments

The writers acknowledge the technical assistance of the L.M.S.G.C..

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