Subaqueous debris flow behaviour and its dependence on the sand/clay ratio: a laboratory study using particle tracking

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Abstract

Subaqueous debris flows were studied through a set of laboratory experiments examining the behaviour within the flow and the effects of varying the clay–sand mass fraction at a fixed water content. They confirm earlier experiments where mobility is enhanced by a lubricating layer and run-out is largely influenced by other mechanisms than the rheological properties of the debris flow itself for high clay content flows. Through particle tracking by high-speed video, a better understanding of the mobility of subaqueous debris flows has been established. For highly coherent flows, the heads of the flows were hydroplaning. In many cases, hydroplaning stretched, and eventually ruptured, the flowing mass. Fitting the observed velocity profiles to Bingham rheology and by comparing with standard rheological measurements of the pre-flow slurries demonstrates very substantial weakening and softening in the bottom shear layer, but not in the overlying plug layer. This effect is attributed to mixing with ambient water. Weakly coherent flows show an intensively fluidized front; the entire head breaks up into a turbulent flow. Behind the head, one finds a dense flow layer where sand grains drop out during the flow and form a depositional layer. The highest mobility is found for slurries with a low yield stress combined with sufficient competence to allow a moderate settlement of sand during flow. Similar mechanisms are likely to operate in natural subaqueous debris flows and may thus provide an additional explanation for the long run-out distances of those flows.

Keywords: gravity flows; debris flows; flow behaviour; sand/clay ratio; laboratory experiment; particle tracking

1. Introduction

Subaqueous slides and debris flows are extremely mobile, sometimes attaining run-out distances of several hundred kilometres on slopes of often less than 1° (Booth et al., 1993; Hampton et al., 1996; Locat and Lee, 2001). Although not yet fully understood, these long run-out distances seem to be facilitated by the presence of a thin basal slurry layer which significantly increases the mobility of the sediment flow (hydroplaning) (Mohrig et al., 1998; Harbitz et al., 2003). So far, the concept of hydroplaning and enhanced mobility...
has been developed for the frontal part of the subaqueous flows; our understanding of how this process develops and controls the flow behaviour further behind remains limited. A second central issue of submarine mass wasting is how the sediment texture or sand/clay ratio influences upon the dynamics of the debris flow and how the slurry properties may change during flow. A classical issue is the case of how slides and debris flows develop into turbidity currents (see e.g. Hampton, 1972; Middleton and Hampton, 1973), as well as the highly debated problem of displacement and deposition of massive sand bodies in deep water (Lowe and Guy, 2000; Shanmugam, 2000; Stow and Mayall, 2000).

Subaqueous laboratory experiments with highly concentrated flows (density in the range of 1450–2000 kg cm$^{-3}$) started with Kuenen (1950) and his flows where he varied the sand/clay ratio. The clay-rich flows were regarded as debris flows and the sand rich ones (low clay content) as high density turbidity currents, although having nearly the same density. Based on the initial work by Kuenen (1950), high density turbidity currents have been thoroughly studied (see e.g. Middleton, 1970, Postma et al., 1988). Compared with high density turbidity currents, few studies have been devoted to subaqueous debris flows (Hampton, 1972; Mohrig et al., 1998, 1999). Recently, Marr et al. (2001) stated that the addition of rather small amounts of clay promoted the generation of highly mobile, concentrated sandy gravity flows presenting many features associated with debris flows. However, while experiments specifically designed to study the internal dynamics of subaerial debris flows have been of great interest and widely discussed (see e.g. Takahashi, 1991; Eckersley, 1990; Major and Iverson, 1999; Iverson, 1997, 2003), few refer to the subaqueous environment (Hampton, 1970, 1972; Marr et al., 2001).

Debris flows, which are rich in sand or even larger clasts such as gravel, are commonly regarded as granular flows. Grain–grain interaction leads to Coulomb-like behaviour and dispersive pressures which dictate the physical behaviour in large-scale modelling (Savage and Hutter, 1989; Norem et al., 1990). Alternatively, grain–grain interactions mediated by the presence of the fluid play a very important role in flow dynamics (Iverson, 1997; Iverson and Vallance, 2001; Iverson and Denlinger, 2001). Behaviour is governed by the effective stresses, which incorporate the interaction between frictional stresses of the interacting solid particles and the pore fluid pressure. Pore fluid pressure can locally increase, resulting in a decrease in shear resistance to flow (Major and Iverson, 1999).

On the other hand, clay-rich debris flows where cohesion rather than Coulomb friction is the dominating force between particles, are treated as “mudflows”, i.e. as non-Newtonian liquids with more or less fixed rheological behaviour (Johnson, 1970; Huang and Garcia, 1999; Imran et al., 2001).

The purpose of this work is to show how the change in sand/clay ratio influences flow behaviour of subaqueous debris flows. This paper reports a set of experiments which addresses these problems, using varying sediment texture (muddy or sandy) and providing for observation of changes in flow behaviour. These experiments represent a continuation of previous work on subaqueous debris flows (Mohrig et al., 1998, 1999; Marr et al., 2001). The application of particle tracking, using high-speed video, supported by measurements of basal pressures (Ilstad et al., 2004b), sought to further our understanding of subaqueous debris flow mobility. Entrainment of water into the head and basal part of the flow was investigated through deviation in measurements of the initial properties of the slurries (before release) and back calculated rheological properties from velocity profiles.

### 2. Methods and materials

#### 2.1. Experimental set-up and procedure

The debris flow experiments were performed in a long channel with smooth transparent walls, suspended inside a larger glass-walled tank (Fig. 1A). The channel was adjusted to a slope angle of 6° for this set of experiments. A granular coated bed with a roughness height of about 1 mm was installed to prevent slip at the bed.

At the beginning of an experiment, the glass-walled tank was filled with water to about 0.5 m above the gate of the sediment tank and 0.16 m$^3$ of the test slurry was added to the sediment tank. The slurries were released into the channel through a 5.3 cm high and 15 cm wide gate in the head tank. The data acquisition system was started when the gate
opened. Sediment reaching the end of the channel dropped into the larger glass-walled tank.

Due to currents induced by the debris flow, the water in the whole tank was clouded by clay particles a few minutes after the experiment. To obtain visibility in the tank the clouded water is slowly replaced with clear water over a period of about 12 h, after which the deposits in the channel are inspected and documented.

Experiments were recorded with video cameras at two cross-sections, while a camera mounted on a rail followed the flow front (Fig. 1B). In the upper section, a high-speed video camera filmed with a speed of 250 frames/s at a resolution of $480 \times 512$ pixels. View-frames from $6 \times 6$ to $12 \times 12$ cm$^2$ were captured, allowing particles in the flow to be identified.

Only particles moving along the plexiglass side wall of the channel could be tracked with the visual technique used here. The smooth walls do not prevent sliding of sand particles, but they cause a friction force that is expected to increase with depth. In the interstitial water, complicated velocity patterns arise due to the no-slip conditions applicable at the wall. Clay has been observed to stick to the side walls in thin layers, but with substantial variations along the channel and from one run to the next. It is clear that the observed velocity profiles (Section 4.2) are influenced by the wall to some degree, but the effect cannot be quantified at present. However, the friction forces at the smooth side wall are significantly smaller than at the rough bottom. Water may be trapped between the debris
flow and the plexiglass wall, reducing wall friction compared to the zone where the debris flow is in contact with the wall. Stretching of the flow (due to higher velocities in the head than in the tail) may reduce the width of the main body of the flow, allowing for high-pressured slurry at the bed to escape along the plexiglass walls. Such intermittent fluid-escape events were indeed observed in some runs, but the analyzed time intervals were not affected by them.

A standard digital video camera was used in the lower section for documentation purposes, recording at a rate of 30 frames/s, and a standard digital video camera mounted on a rail following the front of the debris flow. The front position at a given time can be determined to about 1 cm accuracy from the video pictures taken by the camera moving along with the flow front. Averaging over time intervals of 0.2–0.5 s, a precision of 5% or better can be obtained for the front velocity, which is quite sufficient for the present purposes. The debris flow depth at the front can usually be estimated to the precision of 10–30% from the video pictures at the front and at the downstream fixed location, if the interface between the dense and turbid layers can be determined at all. At the location of the high-speed video camera, the particle velocities at different depths in the flow can be used for this purpose, allowing measurements to a precision of a few millimetres or typically about 10%.

The pore pressures and the total stresses were also recorded on the channel floor in the same cross-sections as for the video cameras (Ilstad et al., 2004b). Data acquisition was performed with a portable computer connected to a National Instruments data acquisition system. This data acquisition system was also used to trigger the high-speed video recording and pressure measurements in order to synchronize them. This allowed for correlation of the observed flow behaviour with the recorded pore pressure and total stress data.

### 2.2. Slurries used in the tests

The sediment slurries used in our experiments are characterized by the mass fractions of water, clay and sand, defined as

\[ m_w = \frac{M_{\text{water}}}{M_{\text{total}}} , \quad m_c = \frac{M_{\text{clay}}}{M_{\text{total}}} , \quad m_s = \frac{M_{\text{sand}}}{M_{\text{total}}} . \]  

For this set of experiments, kaolin clay (Snowbrite) was used. Kaolin clay has a density of 2750 kg m\(^{-3}\). The coarser material in the slurry was a brown fine silica sand with a density of 2650 kg m\(^{-3}\), a median grain size of 330 \(\mu m\) and a geometric standard deviation of 1.5 \(\mu m\). For the purpose of additional flow visualization, coal slag (a black siliceous material produced as a residue from burning coal) was used in small amounts (less than 1% by weight). It had a median grain size near 500 \(\mu m\) and a material density of 2600 kg m\(^{-3}\).

Eight different slurries were mixed, all of which had the same solid content of 65 wt.%, corresponding to a solid volume fraction of 41%. The clay content was varied from 5 to 32.5 wt.% (Table 1). The experimental runs will henceforth be referred to by the mass fraction of clay. Each sediment slurry was prepared by first mixing the required amounts of clay and water in a concrete mixer for about 1 h. The ingredients of the slurries could easily be weighed to high precision. Sand was added incrementally towards the end of the mixing process. Before adding sand to the clay–water mixture, it was verified visually that the clay particles had been suspended homogeneously.

In compositions with low clay content, the slurry had a tendency to settle in the headtank and was stirred continuously until a few seconds before release of the flow. Eight samples of the slurries taken from the surface within the mixer were measured for water content after the mixing procedure. Table 1 shows the mean value and standard deviation from the eight samples of each slurry. Immediate settlement of sand

<table>
<thead>
<tr>
<th>Exp. no.</th>
<th>Water (kaolin)</th>
<th>Clay (%)</th>
<th>Sand (%)</th>
<th>Density (kg m(^{-3}))</th>
<th>Measured water content (wt.%)</th>
<th>Mean</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35%</td>
<td>5%</td>
<td>60%</td>
<td>1680</td>
<td>37.3</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>35%</td>
<td>10%</td>
<td>55%</td>
<td>1690</td>
<td>39.1</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>35%</td>
<td>15%</td>
<td>50%</td>
<td>1690</td>
<td>35.3</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>35%</td>
<td>20%</td>
<td>45%</td>
<td>1690</td>
<td>36.0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>35%</td>
<td>20%</td>
<td>45%</td>
<td>1690</td>
<td>35.8</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>35%</td>
<td>25%</td>
<td>40%</td>
<td>1690</td>
<td>35.6</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>35%</td>
<td>28.7%</td>
<td>36.3%</td>
<td>1690</td>
<td>35.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>35%</td>
<td>32.5%</td>
<td>32.5%</td>
<td>1690</td>
<td>35.2</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Sediment textures as mass fractions of water, clay and sand for the eight experiments, and measured mass fractions of water after mixing.
grains in low clay content slurries may have resulted in a higher measured mean value of the water content in the samples taken from the top of mixed slurries. The standard deviation also increases at low clay content indicating increasing variability within the slurry.

2.3. Processing of high-speed video images and particle tracking

The frame rate of the normal video camera is insufficient for the purpose of particle tracking. However, at maximum speeds of 1 m s\(^{-1}\), particles move at most 4 mm (and usually significantly less) between two subsequent exposures of the high-speed camera. Therefore, ambiguities in identifying particles on two sequential frames may arise, but were found to be rare. Depending on the size of the viewframe, a given particle is typically visible on 4–15 pixels. The camera was carefully adjusted prior to each experiment to avoid image distortion, minimize reflections from the lighting and assure accurate determination of distances.

Some image processing was performed previous to the particle tracking to enhance the image quality and contrast. Software for computer-assisted particle tracking was developed: a particle is picked by means of the computer mouse on the first frame of a sequence to be analyzed and is then followed from one frame to the next, until it either leaves the viewframe or disappears into the interior of the flow (only particles at the plexiglass wall of the channel are visible). This procedure is then repeated for other particles identifiable on the first frame until a sufficient number of tracks have been obtained. In the next step, particles appearing only on the second frame are identified and tracked as described above, and so on. The software records the coordinates of the selected particles for each frame in which it has been identified. These lists can then be processed further with appropriate programs.

Since this manual tracking procedure is rather tedious and time consuming, three time intervals of 20–30 frames or 0.08–0.12 s were selected in the head, body and tail of each flow, in periods of nearly steady flow. As only short time intervals were analyzed for each run, no firm statements can be made about the short-term variability of the velocity profile. The video recordings reveal that the flow depth and velocity do indeed fluctuate, presumably due to three-dimensional flow patterns induced by interfacial instabilities and the wall forces. The analysis time intervals were deliberately chosen within relatively steady episodes because meaningful inferences on the rheology of the slurry would not be possible otherwise.

Furthermore, flows from slurries with more than 20 wt.% clay were found to behave so similarly that only the experiment with the best image quality was analyzed (28.7 wt.% of clay). In order to generate velocity profiles, the viewframes were divided into 16 horizontal bins from the lowest point of detected particle motion to the top of the frame, and the selected particle tracks were assigned piecewise to these horizontal bins. The mean velocity and the standard deviation were evaluated in each bin.

With a number of particle tracks of different lengths in each bin and some tracks crossing over from one bin to a neighbouring one, there is some liberty in the definition of these statistical quantities. The following prescriptions were used:

\[
\bar{u}_b = \frac{1}{N_b} \sum_{p \in b} \sum_f u_{b,p,f},
\]

(2)

\[
s_b = \left( \sum_{p \in b} \sum_f \left( u_{p,f} - \bar{u}_{b,p} \right)^2 \right)^{1/2} / N_b - 1.
\]

(3)

The indices \(b, p\) and \(f\) refer to the vertical bin number, the particle track number and the frame number, respectively, whereas \(i \in \{x,y\}\) refers to the coordinate axes. \(u_{b,p,f}\) is the velocity vector of particle track number \(p\) in bin number \(b\) between frame number \(f\) and \(f+1\). As normalization factor \(N_b\) in Eq. (2), we use the number of tracked particle displacements during the observation interval in bin \(b\), extended over all particles in this bin. While velocity \(\bar{u}_b\) is the average velocity of particle track number \(p\) inside bin \(b\), \(\hat{u}_{b,p}\) represents the expected velocity of particle \(p\) at its mean height above the bed, derived through linear interpolation from the profile of the average velocities:

\[
\hat{u}_{b,p} = u_b + \left[ y_{b,p} - y_b \right] \left( \bar{u}_{b+1} - \bar{u}_b \right),
\]

(4)
with \( \overline{y}_{b,p} \), the average position of particle \( p \) inside bin \( b \) in the direction transverse to the flow, and \( y_b \), the corresponding position of the centre of bin \( b \). In Eq. (4), the positive or negative sign is chosen according to whether the particle is above or below the middle line of its bin. Eq. (3) approximately takes into account that, in zones of rapid shear, the velocity grows across a bin by an amount comparable to the bin-averaged velocity itself.

As our computer-assisted tracking method was rather time-consuming, only a selection of particles could be followed. There is no indication that the essentially random selection of tracked particles influenced the results in a systematic way, but the relatively small number of particles in each bin causes a fairly large random error on the order of 30% of the measured velocity values.

Sub-pixel resolution in the location of the particles could not be attained with our essentially manual analysis procedure. The mean error, \( \delta u \), in the particle velocity determination is estimated as the distance corresponding to one pixel (i.e. between 0.12 and 0.25 mm, depending on the size of the viewframe) divided by the time interval between frames (4 ms), thus between 0.03 and 0.06 ms. Near the bed, the error is a substantial fraction of the velocities and in particular has to be taken into account when calculating the velocity fluctuation by means of Eq. (3): If the measured fluctuating velocities \( u_f \) are decomposed into the true value and the stochastic measurement error as \( u_f = u_f^0 + u_f^\delta \) with \( u_f^0 = 0 \) and \( \sum u_f^2 = (N_f - 1) (\delta u)^2 \), one obtains

\[
\sigma_u^2 = \sigma_u^{02} + (\delta u)^2. \tag{5}
\]

It will be seen in Section 4.2 that this effect is indeed important for correct interpretation of the velocity and fluctuation profiles.

2.4. Scaling to full-size subaqueous debris flows

It should be kept in mind that the results presented in the following sections may not be directly transferable to debris flows in nature. As will be seen, rheological changes in the course of the flow appear to play an important role. The underlying processes may scale quite differently from the dynamic quantities that should obey (distorted\(^1\)) Froude scaling. In view of these unknowns, the following results should be viewed not as exactly scaled miniature versions of natural debris flows, but rather as outlining their possible behaviour.

3. Rheological measurements

3.1. Set-up and procedure

Standard rheological tests were conducted in order to measure the material behaviour. Samples of the slurries were taken before each run and stored in cups of two sizes, which were stirred prior to each test in order to ensure proper mixing. The tests were performed with a dynamic stress rheometer (Rheometrica) equipped with a vane which was lowered into the cup. To avoid wall slip, which has been reported to occur with clay slurries (see e.g. Coussot, 1997), a grid was attached to the outer wall of the cup. The test procedure consisted of imposing different levels of torque on the vane, waiting for a steady regime to establish and recording the rotation rate at each torque level.

3.2. Results

A shear thinning behaviour is seen for shear rates below 20–25 s\(^{-1}\) and is most prominent with high clay contents (Fig. 2A). This behaviour is related to the breaking and reforming of clay particles bonds which dissipates most of the energy, leading to a shear thinning behaviour (Coussot, 1997). From about 25 to 30 s\(^{-1}\), all slurries show an almost constant viscosity. Shear rates up to 120–130 s\(^{-1}\) are relevant for bottom shearing in the debris flow part of the experiments. As the clay to sand ratio increases, an exponential increase in yield strength is observed (Fig. 2B). Some samples were ruined during storage, possibly due to faulty sealing. These samples were prepared again for rheological measurement. This attempt failed, however, since the new remixed slurries behaved slightly

\(^1\) In large debris flows in the oceans, the mean slope angle is much smaller than in our experiments. Accordingly, the gravitational and hence also the inertial forces scale with the vertical distances, but the flow times with the horizontal distances.
differently, perhaps due to small changes in clay mineralogy in a new shipment of kaolin clay. Yield stresses for the untested slurries are therefore interpolated (Fig. 2B).

4. Global features of the laboratory flows

4.1. Flow characteristics and flow behaviour

Sediment textures ranging from sand-dominated to clay-dominated slurries were used to investigate how the flow regime/pattern varied in response to changing sediment texture. According to previous experimental studies (see e.g. Hampton, 1970; Marr et al., 2001), flow behaviour is strongly related to the shear strength of the slurry and the dynamic stresses. The shear strength is related to the type and content of clay minerals, while dynamic stress is a function of flow velocity, which in turn is a function of slurry rheology, volume, slope angle and bed roughness.

Marr et al. (2001) used the term “coherence” to describe “the state of a mixture with respect to the extent of erosion, break-up and water-entrainment at the head under given dynamic stresses”. Thus, the term “coherence” is a dynamic classification that may change during flow in response to variations in shear stresses including internal properties of the slurries. According to Marr et al. (2001), “weakly coherent gravity flows” represent slurries that generate substantial subsidiary turbidity currents; the entire head may dilate and break up into a turbulent suspension. On the other hand, a “strongly coherent flow” experiences limited erosion and break-up, and shows a sharp interface between the gravity flow and the overlying dilute turbidity current. In our experiments with clay contents from 5 to 33 wt.%, we covered the whole range of coherency, from weakly to strongly coherent flow.

Clay-rich flows (28.7 wt.% clay, 36.3 wt.% sand) are characterized by a well defined head-shaped front of approximately 0.2 m length (Fig. 3A). The turbidity current generation at the front is moderate to low and a well defined boundary between the dense slurry and its overlying dilute turbidity current can be followed during the entire flow (Fig. 3B). By increasing the clay content to 33 wt.%, a more pronounced head and slide body appear and less material is eroded and brought into suspension (Fig. 3C). According to Marr et al. (2001), these clay-rich slurries typically form "strongly coherent flows".

![Fig. 2. (A) A series of shear rate–yield stress curves obtained for different slurries with varying clay–sand ratio. (B) Relationship between yield stress and clay content. The line represents the best fit line for the measured yield stresses (dots). Interpolated yield stresses are shown as plus signs.](image_url)
Fig. 3. Pictures from different flows, 7.6 m downslope the head gate. (A) Hydroplaning head of 28.7 wt.% clay with a dilute turbulent cloud on top. (B) Just behind the front (28.7 wt.% clay) and we see the dense stretched layer flowing above the bed with a turbidity current on top. (C) Hydroplaning head of 32.5 wt.% clay. (D) Head of 20 wt.% clay. (E) Just behind the front (20 wt.% clay). (F) Flow within the main body of the flow (20 wt.% clay). We see an incipient drop-out layer of sand at the bed with a slurry flowing on top (the dashed lines show the interfaces between the deposition, the dense flow and the turbidity current). (G) Turbulent head of 5 wt.% clay. (H) Just behind the front of the 5 wt.% clay. Notice the deposited layer at the bed, overridden by the dense flow (dashed lines indicate the interfaces between the layers).
Flow behaviour seems to change gradually as we increase the sand content. slurries with 20 wt.% clay and 45 wt.% sand show a clear tendency for head erosion and break-up, resulting in a well-defined turbidity current (Fig. 3D–F). By further increasing the sand content (15 wt.% clay, 50 wt.% sand), even more prominent turbidity current generation is observed. However, the interface between the dense debris flow and the overlaying dilute turbidity current remains easily identifiable. According to Marr et al. (2001), these types of flow may be characterized as “moderately coherent flows”.

The most sand-rich debris flows (5 wt.% clay, 60 wt.% sand and 10 wt.% clay, 55 wt.% sand) showed an intensively fluidized front with the entire head appearing to break up into a turbulent flow (Fig. 3G). In these types of flow, we were not able to distinguish the main debris flow and the overlying turbidity current in the frontal zone, only some distance behind the front (Fig. 3H). Thus, in accordance with Marr et al. (2001), these flows can be classified as “weakly coherent flows”.

4.2. Analysis of velocity profiles

Tracking of particles was conducted and processed following the procedures described in Section 2.3. Fig. 4 shows one image of the flow, one image of particle tracing and the average velocity over each time interval with standard deviation. Focus is on the dense flow layer near the bed, but the turbidity current and the transitional zone are also briefly discussed below. The dense flow is higher than the view height for some time intervals, but overall the particle tracking captures the essential flow behaviour. For the other flows, at lower clay content, only velocity profiles are shown. A specific description of the velocity profiles of the different debris flow behaviour is given: strongly, moderately and weakly coherent flows. Observations of layer thicknesses and velocities for the time intervals (Table 2), and behind the head (Fig. 5), we find a significant deceleration of the flow for the strongly coherent flows, which will be discussed later (Section 5.2).

4.2.1. Strongly coherent flow

The first time interval (Fig. 4) shows a hydroplaning head riding on top of a thin wedge-shaped water layer. As seen from the velocity profile (x-velocity, Fig. 4), internal deformations are minor and variations in the velocity profile are mainly due to picture resolution (see Section 2.3). A uniform velocity profile is obtained throughout the head, which has a thickness greater than the camera view (65 mm). The velocity (0.85 m s⁻¹) is also the front speed since the entire head moves almost like a rigid block. Farther behind the head (Fig. 4), the thickness of the dense flow has been reduced by a factor of 5–6 with respect to the head. Due to the hydroplaning head, a stretching zone with reduced thickness develops behind the head. The dense flow layer has bed contact with a pronounced zone of shearing localized in the lower part (5 mm). Above this zone, the velocity is rather uniform without any pronounced gradients. The velocity of 0.28 m s⁻¹ in this part is also significantly lower than that observed in the head. Few particles could be tracked in the overlying turbidity current, but altogether they indicate a higher speed relative to the dense flow. Velocity fluctuations increase from the bed up through the dense flow to about 0.05–0.1 m s⁻¹ at the top of the dense flow. By the third time interval, the dense flow thickness has doubled from the previous time interval. The velocity decreased further (0.24 m s⁻¹) and, as in the previous time interval, the zone with pronounced shearing is localized in a narrow zone (5 mm) close to the bed. A relatively uniform velocity fluctuation is found throughout the dense flow. Turbidity current generation at the front is low and velocities are slightly higher than in the dense flow.

Velocities perpendicular to the bed (y-velocity, Fig. 4) show a uniform trend of a slightly downward movement, which may be explained by deformation in the underlying water layer. The next time intervals show no significant perpendicular velocities within the shear layer but some movement above.

To conclude, a rigid head flows on top of a water layer with a uniform velocity throughout the head. The head is much thicker than the stretching zone just behind it, with flow thickness increasing again farther behind. Behind the head, shearing is concentrated in a thin zone near the bed. Velocity in the upper part of the dense flow decreases rapidly behind the head.
Fig. 4. Particle tracking of a strongly coherent flow (28.7 wt.% clay, 36.3 wt.% sand). Three time intervals are tracked at 0.37, 2.1 and 3.9 s behind the front. Particle vectors are between two trailing frames, see Section 2.3, and some image processing has been performed to improve the image contrast. The bar between the $x$- and $y$-velocity shows different layers within the flow. Note different scaling for the $y$-velocity for the turbidity current (upper axis) and the dense flow (lower axis). Expected uncertainties are in the order of the measured values for the $y$-velocities, but average velocities may give strong indications of the flow since most of the uncertainties are given by the picture resolution, see Section 2.3.
4.2.2. Weakly coherent flows

The weakly coherent flows include 5 and 10 wt.% clay, see Fig. 6. The marked head with greater thickness, seen for strongly coherent flows, is now absent (Fig. 3E) and only a turbulent front is visible. A stratified flow, with a dense flow part at the base, is not seen before about 0.5 s behind the front. The first time interval (Fig. 6) represents the first occurrence of a relatively steady flow. Compared to the strongly coherent flow, a more uniform thickness is seen throughout all time intervals with the flow only slightly thicker near the front. The shearing zone is much larger compared to the flow thickness (Table 2), as opposed to in strongly coherent flows where a thin shear zone remains through all time intervals. The 5 wt.% clay flow shows an almost uniform velocity (x-velocity, Fig. 6) through all time intervals in strong contrast to the strongly coherent flow where the velocity decreases behind the front. The reduced velocity in the boundary zone between the dense flow and the turbidity current is a result of wall effects (Section 2.1). The 10 wt.% clay flow shows a similar trend as the strongly coherent flows, with a reduction in speed behind the front.

The turbulent front results in a significant turbidity current compared to in strongly coherent flow. The turbidity current has slightly higher velocities than the dense flow, as was also seen in the strongly coherent flow.

A pronounced downward velocity component is observed within the shear zone for the weakly coherent flow (y-velocity, Fig. 6), related to depositional processes. The weakly coherent flows show deposition during flow, a feature not seen in strongly coherent flow. Deposition occurs continuously as sand is dropped from the shear zone, building up the non-moving depositional layer at the bed (Fig. 8).

To conclude, in weakly coherent flows a turbulent head moves downslope, trailed by a density-stratified flow with a dense lower layer. Turbidity current generation is high from the turbulent head. The dense flow part shows a more uniform longitudinal thickness compared to the strongly coherent flow. Shearing is concentrated in the lower part of the flow, accompanied by downward particle movement, which results in deposition of sand grains.

Table 2

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Shear zone thickness (mm)</th>
<th>Dense flow thickness (mm)</th>
<th>Max. velocity (m s⁻¹)</th>
<th>Depth-average velocity (m s⁻¹)</th>
<th>Hampton number</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 wt.% clay, 60 wt.% sand</td>
<td>1.4</td>
<td>25</td>
<td>30</td>
<td>0.32</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>3.8</td>
<td>10</td>
<td>21</td>
<td>0.41</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>10</td>
<td>20</td>
<td>0.39</td>
<td>0.27</td>
</tr>
<tr>
<td>10 wt.% clay, 55 wt.% sand</td>
<td>1.2</td>
<td>10</td>
<td>35</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>10</td>
<td>20</td>
<td>0.21</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>10</td>
<td>20</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<tr>
<td>15 wt.% clay, 50 wt.% sand</td>
<td>1.1</td>
<td>20</td>
<td>60</td>
<td>0.35</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>10</td>
<td>20</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>10</td>
<td>20</td>
<td>0.15</td>
<td>0.10</td>
</tr>
<tr>
<td>20 wt.% clay, 45 wt.% sand</td>
<td>0.34</td>
<td>5</td>
<td>&gt;60</td>
<td>0.57</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>20</td>
<td>45</td>
<td>0.33</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>15</td>
<td>40</td>
<td>0.16</td>
<td>0.10</td>
</tr>
<tr>
<td>28.7 wt.% clay, 36.3 wt.% sand</td>
<td>0.37</td>
<td>5</td>
<td>&gt;65</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>5</td>
<td>15</td>
<td>0.28</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>3.9</td>
<td>5</td>
<td>30</td>
<td>0.24</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The Hampton number (Eq. 6) for the flows are calculated showing a laminar flow regime (less than 1000) for all flows.

4.2.2. Weakly coherent flows

The weakly coherent flows include 5 and 10 wt.% clay, see Fig. 6. The marked head with greater thickness, seen for strongly coherent flows, is now absent (Fig. 3E) and only a turbulent front is visible. A stratified flow, with a dense flow part at the base, is not seen before about 0.5 s behind the front. The first time interval (Fig. 6) represents the first occurrence of a relatively steady flow. Compared to the strongly coherent flow, a more uniform thickness is seen throughout all time intervals with the flow only slightly thicker near the front. The shearing zone is much larger compared to the flow thickness (Table 2), as opposed to in strongly coherent flows where a thin shear zone remains through all time intervals. The 5 wt.% clay flow shows an almost uniform velocity (x-velocity, Fig. 6) through all time intervals in strong contrast to the strongly coherent flow where the velocity decreases behind the front. The reduced velocity in the boundary zone between the dense flow and the turbidity current is a result of wall effects (Section 2.1). The 10 wt.% clay flow shows a similar trend as the strongly coherent flows, with a reduction in speed behind the front.

The turbulent front results in a significant turbidity current compared to in strongly coherent flow. The turbidity current has slightly higher velocities than the dense flow, as was also seen in the strongly coherent flow.

A pronounced downward velocity component is observed within the shear zone for the weakly coherent flow (y-velocity, Fig. 6), related to depositional processes. The weakly coherent flows show deposition during flow, a feature not seen in strongly coherent flow. Deposition occurs continuously as sand is dropped from the shear zone, building up the non-moving depositional layer at the bed (Fig. 8).

To conclude, in weakly coherent flows a turbulent head moves downslope, trailed by a density-stratified flow with a dense lower layer. Turbidity current generation is high from the turbulent head. The dense flow part shows a more uniform longitudinal thickness compared to the strongly coherent flow. Shearing is concentrated in the lower part of the flow, accompanied by downward particle movement, which results in deposition of sand grains.

![Fig. 5. Plug velocity development in the dense flow. Notice the narrow band enclosing all flows with clay content above 5 wt.%](image-url)
4.2.3. Moderately coherent flows

The 15 and 20 wt.% clay flows represent moderately coherent flow (Fig. 7). They show a transition in flow behaviour between the strongly and weakly coherent flow.

In contrast to strongly coherent flows, no water layer is visible beneath the head of these flows. Similarly, as in the strongly coherent flows, the moderately coherent flow shows a decreased thickness and velocity behind the front. In moderately...
coherent flows, the front gradually changes from a rigid head, as in the strongly coherent flow, to a fluidized front as seen in weakly coherent flows.

The shear zone, which in the strongly coherent flow is concentrated in a narrow band, now expands to include a larger proportion of the flow thickness. The transition is also well documented in the velocity perpendicular to the bed (y-velocity, Fig. 7). The first signs of downward movement are seen, reflecting the drop-out of sand during flow.

Fig. 7. Velocity profiles of medium coherent flows. Note the difference in height in the velocity profiles.
Thus, we see a gradual change in important flow characteristics with respect to rigidity of the head (increased fluidization), shear zone thickness (increased) and drop-out of sand. In conclusion, the transition from strongly to weakly coherent flows shows no abrupt changes.

4.3. Deposition and depositional pattern

A characteristic feature of the most sand-rich slurries is the massive deposition of material during flow, starting almost immediately behind the head (Figs. 3F, H and 8). Due to the rather uniform grain size distribution of the sand material used in the experiments, the lower drop-out layer showed a rather uniform and ungraded structure. In slurries with 5 wt.% clay, the settling of the sand particles occurs rather rapidly and the thickness of the depositional layer increases behind the front. By increasing the clay content, the accumulation rate of the depositional layer decreases (Fig. 8). The most pronounced deposition occurs in the “weakly coherent flows”. A well-developed distribution of the depositional layer is observed in the slurry with 5 wt.% clay, while the thickness is rather similar for the slurries containing 10 and 15 wt.% clay, respectively (Fig. 8). The “moderately coherent flows”, above 15 wt.% clay, show much less settling or deposition, with sandy deposits limited to the front part of the flow. The strongly coherent flows do not show any sign of settling of sand during flow. For this type of flow, the high clay content prohibits any settling of material during flow.

Final depositional thicknesses were measured one day after the flow event (Fig. 9). In all experiments, some mass reached the end of the channel and dropped into the larger glass walled tank (Fig. 1A). The clay-rich slurries or “strongly coherent flows”
shows a final deposit which is thickest near the gate and thins down the slope, with outrunner blocks in front of the main non-hydroplaning body of the slide (Fig. 9). As the mass fraction of clay is reduced (“moderately coherent flow”), continuous final deposition is seen, with a thinning non-hydroplaning rear part, and a front deposition with uniform thickness. At even lower clay content (“weakly coherent flow”), final deposition has a more uniform thickness along the entire channel. The lowest clay content deposition shows a change in pattern by thickening in the first 2.5 m and then thinning further down.

4.4. Front velocity

Front speeds along the slope are measured based on video recordings (Fig. 10). The most clay-rich flows move with the lowest velocities, 0.77 m s$^{-1}$ in the upper part of the slope, decreasing to 0.68 m s$^{-1}$ towards the end. A similar pattern of decreasing velocity is also observed for the other clay-rich or strongly coherent flows, although these flows show somewhat higher velocities. The moderately and weakly coherent slurries show a higher and also more uniform velocity throughout the entire flow (Fig. 10).
In summary, a decreasing front speed is observed for strongly coherent flows, while an almost uniform front speed is observed for moderately and weakly coherent flows, thus the latter flows rapidly attain their terminal velocity.

5. Discussion

Based on the flow characteristics, we discuss the strongly and weakly coherent flows and state that a gradual transition occurs between these flows, characterized by the moderately coherent flows.

5.1. Flow regime and frontal acceleration

Table 2 shows the Hampton number, $H$ (Hiscott and Middleton, 1979), given by

$$H = \frac{\rho_s U^2}{\tau_y}$$

where $\rho_s$ is the slurry density, $U$ is the flow speed and $\tau_y$ is the slurry yield strength. For a critical Hampton number of 1000, a viscoplastic laminar flow turns into turbulent flow (Hiscott and Middleton, 1979). From the calculated values of the Hampton number (Table 2), we see that all the dense flows in this study are within the laminar regime.

The front of the strongly cohesive flow (Fig. 10) shows a marked deceleration along the slope. How is this affecting the flow dynamics? Using the front velocity, $v$, for the 28.7 wt.% clay run (Fig. 10), we calculate the acceleration, $a$, as

$$a = \frac{dv}{dt} = \frac{dv}{dx} \frac{1}{x} = \frac{(0.78 - 0.93) \text{ ms}^{-1}}{8 \text{ m}} \frac{0.85 \text{ m s}^{-1}}{= -0.16 \text{ m s}^{-2}}$$

Looking at the ratio between the gravitational pull along the slope and the inertial term, $\rho_s a$, we find

$$\left| \frac{(\rho_s - \rho_w)g \sin(6^\circ)}{\rho_s a} \right| = 26,$$

where $\rho_w$ is the water density and $g$ is the acceleration of gravity. The gravitational pull is 26 times the inertial term for the flow with the highest deceleration.

This shows that the frontal deceleration has little effect on the flow, and that the gravitational pull is the dominant force governing flow downslope.

5.2. Strongly coherent flow

Strongly coherent flows show a distinct head riding on top of a thin layer of water, i.e. hydroplaning. Hydroplaning is the phenomenon associated with a dynamic pressure generated at the front which permits the intrusion of a thin layer of lubricating water between the debris flow and the bed. Previous experiments have suggested that the basal shear stress is reduced due to this basal lubricating layer of water or mud slurry (Mohrig et al., 1998). Mohrig et al. (1999) further investigated this effect by performing a set of experiments where they found that subaerial debris flows extensively remobilized antecedent debris flow deposits, while the corresponding subaqueous debris flows ran over antecedent debris flow deposits with no detectable remobilization. Harbitz et al. (2003) studied this lubricating layer theoretically with a two-layer Couette flow and found that stresses in both the low-viscosity lubricating layer and the high-viscosity deforming bed below were substantially reduced. However, while this lubricating water layer is clearly visible under the front, the major question is how a lubricating layer evolves further behind the front, underneath the main debris flow body.

High clay content debris flows have a sufficiently high yield stress to establish a distinct head (Fig. 11A). The head is hydroplaning on a water layer and the low permeability prevents water dissipation upward through the head. Farther behind the head, a plug flow is observed with a pronounced zone of shearing in a narrow region at the bed (Fig. 4). An important and as yet unsolved task is to find the rheological properties of this lubricating layer.

Based on rheological measurements of the yield strength, a yield thickness, $h_y$, for the different slurries may be calculated as (see e.g. Hampton, 1970; Huang and Garcia, 1999)

$$h_y = \frac{\tau_y}{(\rho_s - \rho_w)g \sin \theta}$$

The calculated yield thickness is compared to the observed flow height from the high speed pictures.
For slurries with 15 wt.% clay and higher, the flow height is significantly lower than the yield thickness. This is only possible if the yield stress in the shear layer was lower than the initial yield stress when the slurry was released from the tank. Hence, the shear layer properties have to have altered during the flow. This is shown in a detailed idealized velocity profile for high clay content flows (Fig. 11B). We have a lubricating layer, as suggested by several others (see e.g. Mohrig et al., 1999; Harbitz et al., 2003), with different properties from the overlying “plug”. We now need to determine the origin and development of this lubricating layer.

The hydroplaning front flows on top of a water layer, which supplies water for a lubrication layer near the bed. With high clay content we see a layer of clear water underneath the front (Figs. 3A and 4). Farther behind we see small amounts of sand and clay incorporated into this water layer. In the stretching zone behind the head, the basal water layer is transformed into a mud layer. The debris flow sediments supported by the lubricating water layer are eroded from below and mixed into the lubricating layer (Fig. 12), increasing its viscosity. The greatest erosion will occur behind the head since in this zone the debris flow will have tensile stresses combined

Table 3
Calculated yield thickness, $h_y$, and the observed flow height at the last time interval of each slurry composition

<table>
<thead>
<tr>
<th>Clay content (wt.%)</th>
<th>Measured yield stress (Pa)</th>
<th>Calculated yield thickness (mm)</th>
<th>Observed flow height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>42</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
<td>71</td>
<td>40</td>
</tr>
<tr>
<td>28.7</td>
<td>125</td>
<td>177</td>
<td>30</td>
</tr>
</tbody>
</table>
with high shear stress at the base. The tensile stresses will reduce the pore pressures, keeping the effective mean stress unchanged in the debris flow, resulting in a high pressure gradient to the lubricated water layer. Diffusion of water into the debris flow from the lubrication layer will increase the pore pressures, thus reducing the effective stresses, and open up small cracks in the sole of the debris flow. These cracks will significantly increase the erosional effect from the base of the debris flow (Fig. 12). By plotting the velocity behind the head (Fig. 5), we find a significant deceleration of the flow behind the head. This stretching will also induce shear planes in the flow, and possibly localized shearing, an explanation for the velocity fluctuations in the stretching zone of the highly coherent flow (Fig. 4 (second time interval)). Thinning of the flow (necking) has been observed also in the lateral direction of unconfined experimental flows (Ilstad et al., 2004a).

Previous work by Coussot (1995, 1997) investigating clay–water slurries with and without added sand particles has shown that the yield stress increases approximately exponentially as the solid fraction increases. Other studies of the influence of water content on the rheological behaviour of slurries demonstrate that small changes alter yield strength and viscosity by orders of magnitude (Kuenen, 1951; Hampton, 1972; Locat and Demers, 1988; O’Brien and Julien, 1988; Major and Pierson, 1992; Parsons et al., 2001). Mixing small volumes of clay into the basal lubricating layer will likewise create a large increase in yield stress and viscosity compared to the pure water in the frontal areas, while still having much lower yield stress and viscosity than the overlying debris flow.

Thus, a gradual increase in rheological properties in the lubricating layer will occur behind the head.

Based on a two-layered Bingham model (App. A), the yield stress and viscosity are calculated for the lubricating layer for 28.7 wt.% clay at 2.1 and 3.9 s (Table 4).

This lubricating layer will most likely be present from the front of the head to a finite distance behind the head. Upslope of the lubricating layer, the slurry will flow as a regular viscoplastic flow with a shear layer, which has rheological properties inherited from the initial failed masses. The transition point between regular plastic flow, and flow with a basal lubricating layer, will move downslope due to the fact that only a finite volume of water is trapped underneath the head.

To further illustrate this, we look at the pressure development at the base of the 28.7 wt.% clay flow (Fig. 13) as also described in Ilstad et al. (2004b). Both the total stress and the pore pressure underneath the debris flow are measured. The pressure development shows the stagnation pressure building up before the front arrival; the front and the trailing masses, up to 11.5 s, are carried by a liquefied basal layer, thus giving a low basal friction. Farther behind, the total stress rises with only a slight increase in pore pressure, indicating an increase in basal friction since the flow matrix is carrying parts of the debris flow weight. We assume that the latter zone represents regular viscoplastic flow.

### Table 4
Calculated yield stress and viscosity in the lubrication layer of flow with 28.7 wt.% clay based on shear zone thicknesses and velocities given in Table 2

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Yield stress (Pa)</th>
<th>Viscosity (Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-flow</td>
<td>125</td>
<td>0.86</td>
</tr>
<tr>
<td>2.1</td>
<td>4.2</td>
<td>0.08</td>
</tr>
<tr>
<td>3.9</td>
<td>9.9</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Thus, we observe the hydroplaning front followed by
the lubricated zone and a zone with regular visco-
plastic flow furthest behind the front (Fig. 14). These
are observations from laboratory experiments and
further work needs to be done to make them
applicable to real flows in the field.

5.3. Weakly coherent flows

In contrast to the strongly coherent flows, weakly
coherent ones possess a turbulent front (Fig. 3G).
Based on velocity profiles and particle tracking of
weakly coherent flows, a conceptual debris flow
behaviour is found (Fig. 15). As described in Section
4.1, the front displays an intensively fluidized and
turbulent behaviour where water is entrained. This
water entrainment suppresses all hydroplaning before
the water is allowed to penetrate underneath the
subsequent dense flow. These low clay content debris
flows have a very low yield strength, which permits
grain settlement during flow (Fig. 8). Deposition is
observed to be continuous during flow and builds up a
thickening depositional layer beneath the dense flow.
What determines this deposition of sand?

Kuenen (1951) investigated settling velocities of
sand grains in clay suspensions of various densities
and found decreased velocities compared to Stoke’s
law. Competence (largest supported grain size) of
debris flows was further studied by Hampton (1975),
who found that the competence was determined by the
yield strength and density of the clay suspension.
Examining the settling of a sand particle within a non-
flowing clay–water slurry gives an approximate
estimate of the yield stress needed to support a sand
particle of diameter, \( d \), as

\[
\tau_y = (\rho_s - \rho_m) \frac{gd}{6\alpha}
\]

where \( \alpha \) is the critical resistance coefficient with a
value of 3 for most practical applications. With a
particle diameter of 330 \( \mu \)m, this predicts a yield stress
of 0.28 Pa which corresponds to a clay content of about
11 wt.% in a clay–water suspension (Coussot, 1995).
Within the sheared part of the flow, sand particles will

![Fig. 13. Pressure measurements at the base of a clay-rich debris flow (25 wt.% clay) with interpreted flow behaviour as pressure develops during the flow.](image1)

![Fig. 14. Strongly coherent flow with zones of behaviour.](image2)
tend to settle, but Hampton (1975) showed in his experiments that particles are also supported in the sheared region even though the competence decreases. Iverson (1997) also states that particles may be regarded as part of the fluid phase if the time required for "Stokesian" settling of the solid phase exceeds flow duration. This indicates that sand may be transported for long distances, or alternatively slowly settle out during flow as seen in our experiments.

The dense part of weakly coherent flows, in contrast to highly coherent ones, flows without a basal lubricating layer because hydroplaning is suppressed at the front. The mobility of these flows is instead due to the low yield stress and low viscosity of the slurry. Recent experiments of Ilstad et al. (2004b) measuring total stresses and pore pressures in subaqueous flows show high pore pressure behaviour at the front and in the flow interior. Similar experiments in terrestrial experimental flows (Major and Iverson, 1999) also show pore pressures nearly sufficient to cause liquefaction to persist in the flow interior, while the flow perimeter exhibited low or no excess pore pressure. Thus, friction is concentrated in the flow margins. This major difference in the front behaviour is mainly due to the fact that subaqueous flows are surrounded by water, which is entrained at the front, while terrestrial flows have no additional water available at the front. Despite this difference at the front, the behaviour in the flow interior is similar. The question is to what extent we may use the present theory of terrestrial flows and what needs adaption to the subaqueous environment.

It has been argued (Iverson, 1997; Iverson and Denlinger, 2001; Iverson, 2003) that a fixed rheology cannot provide an explanation of sand-rich debris flow motion, because the evolving behaviour is too complex to be represented by such models. It should be noted that the high clay content slurries in our study show a good repeatability in rheological tests, while the low clay content slurries show large variations with the same test procedures. Coussot (1997) also lists a number of difficulties, e.g. sedimentation and migration of particles, when working with rheological measurements on mud suspensions with high concen-

![Fig. 15. (A) Observed flow behaviour in the front and near front for weakly coherent flows. (B) Conceptual flow profile in weakly coherent flows.](image-url)
trations of non-cohesive particles. From the velocity profiles of the weakly coherent flows (Fig. 7) we see a gradual change to a more viscous flow profile with decreasing clay content. We therefore suggest that weakly coherent flows fit into the Coulomb mixture theory of Iverson (1997) where pore-fluid pressure is the critical “state variable”. This theory reduces to that of a viscous fluid when the pore pressure is sufficient for complete liquefaction and to a Coulomb solid when pore pressure is absent.

Flow is dominated by high pore pressure nearly sufficient for complete liquefaction, giving a near viscous flow. Since settling occurs in the flow, sand concentration will increase towards the bed, giving deposition during flow. The clay moves with the fluid phase and this will give a reduced clay content in parts of the deposits and increased clay content in other parts compared to the initial clay content before run-out.

5.4. Mobility and depositional pattern

Classically, massive structureless sands have been classified as turbidites resulting from rapidly depositing turbidity currents (Kneller and Branney, 1995), but recently it has been proposed that such deposits may also result from sand-rich debris flows (Shanmugam, 1996). The discussion on the importance of these processes has partly been triggered by the discussion of the origin of massive clay-rich sand deposits in deep water environments (Stow and Johansson, 2000; Shanmugam, 2000).

Through this set of experiments we have studied the mobility of slurries with the same water content, only changing the clay to sand ratio. Depositional thicknesses along the suspended channel (Fig. 9) and the build-up of a depositional layer during flow for the weakly coherent flows (Fig. 8) shows evidences of the depositional processes. Concerning the mobility of the different flows, we look at their ability to move large volumes of sediment over long distances. Looking at the deposited volumes upslope and downslope 9 m (the end of the suspended channel) as the clay to sand ratio is changed (Fig. 16), we find that the most mobile flows had 10 and 15 wt.% clay and mobility decreases for both higher and lower clay contents. For the 5 wt.% clay, flow mobility is restricted by rapid sedimentation during flow. At high clay content, mobility is restricted by high flow resistance (viscosity and yield strength). Thus, most mobile flows have a sufficient strength to suppress rapid sedimentation during flow, but still a low resistance in the flow interior compared with strongly coherent flows.

It has also been shown that the transition from debris flow to turbidity current is an inefficient process for mass transport (Hampton, 1970; Mohrig and Marr, 2003). Mohrig and Marr (2003) state that the net sediment transfer from the debris flow to the turbidity current is small since the process (occurring at the front) is limited to a small fraction of the volume. We therefore suggest that massive structureless sands may be formed by sandy debris flow.

6. Conclusions

The dynamics of subaqueous debris flows were studied using a set of laboratory experiments. These experimental debris flows were investigated using a set of combined techniques. Particle tracking analysis with a high-speed camera was employed to collect data on the velocity field for different positions and at different times inside the debris flow and at the level of the turbidity current layer. Other techniques included rheological tests on the slurry and a study of the geometry of the final depositional pattern. The debris flow was also monitored with both fixed and moving cameras. Dependence of the dynamics on the composition was studied by changing the amount of clay versus sand in the initial slurry.
At high clay contents (more than 20 wt.% clay), one observes an apparent coherent flow of the material. A thin water layer intrudes underneath the front part of the debris flow, providing an efficient lubrication effect. This leads to stretching of the main bulk of the flow and may lead to a complete detachment of the head from the rest of the debris flow. The head itself, however, remains essentially rigid. The thin water layer underneath the head is a supply for water at the base of the flow. Erosion from the basal surface of the overlying sediments turns this water layer into a lubricating slurry layer. Erosion is enhanced by a significant stretching of the sediment following just behind the head, which creates a suction in the debris flow. Diffusion of water from the basal lubrication layer into the sole of the debris flow reduces the effective stresses and opens small cracks in the debris flow which increases erosion from the basal surface of the dense flow. This is thought to be the main process whereby sediments are mixed into the basal lubricating layer. In agreement with laboratory measurements, there are indications that the yield stress and viscosity of the clay slurries show a dramatic dependence on the amount of water. A lubricating layer with decreased yield strength and viscosity compared to that of the main bulk of sediments in the dense flow is formed at the base, enhancing the mobility. At some distance further behind the head, no water is available for mixing at the base and a uniform viscoplastic flow will occur.

As the amount of clay is reduced, the head of the debris flow loses its rigid behaviour and shows only a low degree of cohesion, whilst the middle and the final parts behave more like the clayiest flows. We observed a thin depositional basal layer composed mainly of sand, which develops from the frontal part of the debris flow. For still lower clay contents (less than 15 wt.% clay), the sediment disintegration and water entrainment proceed rapidly at the head of the debris flow. Slurry yield stress is low enough for particle settlement within all parts of the flow. The debris flow is observed some distance behind the head. Continuous deposition of mainly sand develops during the flow and is linked to the competence of the slurry. Viscous effects are dominant compared to the Coulomb frictional behaviour within the debris flow. From the present experiments, one can state that the flow and depositional features follow a coherent pattern as a function of the composition. On the other hand, quantitative knowledge of the rheological and physical properties of the sediment during the flow still lacks a precise basis.

With respect to mobility we see an optimum for flows with a low yield strength combined with a competence, which allows for sand transport over long distances. Highly coherent flows may generate hydroplaning blocks, which may travel long distances beyond the main deposit.

We see from our experiments that the bulk of the sediment flows downslope with an almost constant density in the basal flow layer. Changing the clay–sand ratio in the slurry does not influence the main transport mechanism of the dense flow. The Hampton number for all of the flows lies in the laminar regime, allowing the main bulk of the dense layer to flow without mixing with the overlying turbidity current. Erosion, break-up and dilation of dense flow is restricted to the front, which limits turbidity current generation. Intrusion of water underneath the front forming a basal lubricating layer enhances the flow mobility but does not affect the density of the main bulk of the sediments. In our view these flows should be named debris flows and deposition from such flows are debrites.

Acknowledgements

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Appendix A. Lubricating layer properties

Assuming that the plug layer has a significantly higher yield stress and all shear deformation occurs in the lubricating layer, a two-layer Bingham flow model is derived to examine the properties of the lubricating layer (Fig. A.1). With a sufficiently high yield stress in the upper layer, we have plug flow; shear stress in the shear layer then becomes:

$$\tau_{xy} = (\rho_2 - \rho_w)gh_2\sin\alpha + (\rho_1 - \rho_w)gsin\alpha(h_1 - y)$$  \hspace{1cm} (A.1)

Flow in the shear layer follows a Bingham flow model with the assumption $\tau_{y1} \leq |\tau_{xy}|$:

$$\tau_{xy} = \left(\frac{\tau_{y1}}{\mu_1} + \mu_1\right)\frac{du}{dy}$$  \hspace{1cm} (A.2)

Using the boundary conditions $u(0) = 0$ and $u(h_1) = U$, the following relationship is found for yield stress and viscosity in the shear layer:

$$\tau_{y1} = (\rho_2 - \rho_w)gh_2\sin\alpha + \frac{(\rho_1 - \rho_w)gh_1\sin\alpha}{2} - \frac{U}{h_1\mu_1}$$  \hspace{1cm} (A.3)

Then, a proper relationship between the shear stress and the viscosity found by rheological tests needs to be added before we can find the properties of the lubricating layer. Rough estimates of the lubricating layer properties (Table 4) may be found by assuming a simple linear relationship between yield stress and viscosity.

References


