On the frontal dynamics and morphology of submarine debris flows

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Abstract

Several submarine debris flows show an apparently chaotic frontal part with blocks of variable size (from roughly tens to some hundreds of metres) located some distance beyond the front of the main deposits. This outrunner phenomenon was studied both in the field and in laboratory experiments. Depositional patterns in a field case (Finneidfjord, northern Norway) are classified from the outer distal part of the debris flow to the outermost outrunner block. Similar patterns were found in experimental debris flows, and we suggest that flow processes in the laboratory are applicable to the field example. Theoretical investigations are applied to assess frontal dynamics and especially the formation and motion of outrunner blocks. As the front of the debris flow pushes through ambient water, a combination of front pressure and lift force allows for intrusion of a water layer underneath the front (hydroplaning). This water layer reduces basal friction and induces tensile stresses farther behind the front, leading to a possible detachment and decoupling with respect to the main slide body. These outrunner blocks show an increased mobility compared to the main slide body and deposition of such blocks may occur far away from the main slide body.

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1. Introduction

Recent investigations of subaqueous mass flows on continental slopes and in fjords show a wide range of morphological features in the frontal part of the deposit (Locat and Lee, 2001). In particular, the use of side scan sonar and swath bathymetry mapping tools reveals the much more complex nature of the subaqueous mass flows than has previously been documented by single-channel seismic profiling and coring. Of particular interest is the observation of outrunner blocks, which are rafts of material origi-
nated from a debris flow but separated from its front by distances that can be in the range of tens of kilometres.

Interestingly, subaqueous laboratory experiments with debris flows show remarkable similarities with deposits at the front of submarine debris flows. In particular, recent experiments with clay-rich slurries reveal high mobility of the frontal part due to the formation of a lubricating water layer, a process called hydroplaning (Mohrig et al., 1998). Chunks of material can decouple from the frontal part of the debris flow, move faster, and finally come to rest as an irregular array of blocks, well separated from the main body of the debris flow deposit. The laboratory experiments provide a means to understand the formation and flow of outrunner blocks, as well as frontal dynamics of subaqueous debris flows in general.

To our knowledge, only a few studies have been devoted to a quantitative understanding of the frontal dynamics of submarine debris flows (Hampton, 1970; Mohrig et al., 1998; Marr et al., 2001; Mohrig and Marr, 2003). Most of the published contributions have been essentially descriptive, and even these studies are relatively scarce, probably reflecting the difficulty in making the observations. A study by Prior et al. (1984) concerning depositional characteristics of a submarine debris flows in Kitimat Fjord, Canada, describes the slide morphology and suggests depositional processes. These suggestions have later been used as explanations for outrunner blocks found on the continental slope (Nissen et al., 1999; Kuijpers et al., 2001). The study by Prior et al. (1984) gives characteristics of the debris flow where the main slide body flowed a finite distance, coming to rest on the fjord bottom. The outermost distal lobe is significantly thinner than the trailing main body, which suggests that it had sufficient momentum to spill out from the main lobe over the original sea floor, and that further flow was supported by high water content in the marine sediments. Outrunner blocks are suggested to originate during the same process. Prior et al. (1984) also report scarcely observable glide tracks with linear patches of debris left behind by the outrunner block. Johns et al. (1986) also studied the outrunner block in Kitimat Fjord and, as a flow mechanism, they suggested high pore pressure, implying reduced effective stresses, thus reducing shear stresses on the block. However, they concluded that the mechanisms of motion were not fully explained.

In the present paper, the dynamics of a debris flow front and the formation (detachment) and behaviour of outrunner blocks in subaqueous debris flows are investigated. Although the concepts expressed in the present paper could be applicable to a variety of cases, we concentrate on the 1996 Finneidfjord slide in northern Norway, which has been the subject of detailed studies over the last few years (Longva et al., 2003). This slide presents a frontal fragmented distribution of deposits comprising outrunner blocks. A set of laboratory debris flow experiments (approximate scale 1:200) producing artificial outrunner blocks has been performed as a background for the interpretation of the field data. The experiments build on previous laboratory studies of subaqueous mass flows (Mohrig et al., 1998, 1999; Marr et al., 2001). Special emphasis is given to the control mechanisms for the formation of outrunner blocks, the resisting forces during flow, the runout, and the velocity, in addition to the stability of the block.

2. The Finneidfjord slide

A shoreline slope failure took place at the head of a fjord in northern Norway on June 20, 1996 involving about 1 million m$^3$ of sediment, of which 90% was below sea level (Fig. 1). Downslope movement of the slide masses resulted in considerable damage to nearby infrastructure and houses on land. The slide has previously been investigated by several authors (Janbu, 1996; Gregersen, 1999; Longva et al., 2003). Here, only the main features of the slide event are briefly discussed, focusing on the outer distal part. The initial slide was caused by detachment along a weak layer, which in turn was due to introduction of excess pore pressure. The initial slide changed the slope angles enough to trigger a quick-clay slide. The failed section involved a cap of Holocene silty clay over late glacial clay with the initial detachment within the Holocene succession.

The slide morphology is divided into four different zones that depend on the depositional features (Fig. 1). Zone A consists of the main bulk of the sediment
Fig. 1. Finneidfjord slide with slide morphology divided into zones. Zone A: Main lobe. Zone B: Zone with scattered blocks. Zone C: Glide zone. Zone D: Main outrunner block. Average bottom slopes along the slide and glide path are shown in the lower panel.
deposited in a lobe where the average slope angle is approximately 2.86°. This main lobe extends a distance of 1 km down the fjord from the slide escarpment to a water depth of 45–50 m, where bottom slope is less than 1°. Most likely, only parts of the total sediments were completely remoulded since the surface of the main lobe displays rafted blocks.

Further out, deposition becomes more scattered (Fig. 1, zone B) and individual blocks are spread out in front of the main lobe. These outrunner blocks have travelled ahead and outside the main lobe, and thus evidently had a more mobile behaviour than the main slide lobe. The larger blocks are typically elongated, 40–70 m long, 10–20 m wide, and 1–2 m thick. The average slope in this zone is 0.94°.

Downdip of zone B, the fjord bottom is smooth and flat with an average slope of only 0.46°. The largest block (110×60×2 m) is found more than 1.4 km downdip from the debris lobe, where it stopped on the flank of a moraine ridge (zone D). Thus, without any barriers in the flow path, the runout of the block would probably have been even longer. Swath bathymetry reveals a very shallow depression of about 10 cm on the seafloor (Fig. 1), which is interpreted as the glide track from the block. The glide track stretches from the main slide lobe and follows the deepest part of the fjord, always in the direction of the maximum gravity pull. Along the glide path of the large block, smaller blocks have been found (zone C), which may represent other glide blocks in the same path or breakoffs from the larger block. Breakoffs may be a result of block contact with the bed while gliding along the path.

During 2001, a coring program was carried out including one core through the largest outrunner block. Cores were obtained using a battery-assisted, hydraulic-driven vibracore supported in a stabilizing frame.

Our sediment description (Fig. 2) shows slightly bioturbated but otherwise undisturbed sediments in the lower part, and preserved original layering with ice-dropped gravel in the upper part. Visual observation of the split core found a sharp transition between the block and the original sea floor sediments at about 130 cm core depth.

Estimates of undrained shear strengths were obtained by fall cone tests, which were performed at 10 cm intervals down the core except at the disturbed ends. From 0 to 110 cm, the shear strength increases from 7 to 20 kPa, except for a zone between 50 and 80 cm, where the shear strength is slightly decreased. Below 130 cm, there is a rapid drop that reaches 10 kPa at 135 cm, corresponding to the depth where the original seabed is found under the block. From 135 to 160 cm, the shear strength shows small variations around a value of 10 kPa. Below 150 cm, the shear strength increases to 14.3 kPa at 180 cm.

X-rays and photographs of the core show that the original layering is preserved in the block. During the sliding process, a complete remoulding of the sediments would have destroyed this layering. Small cracks and fissures orientated parallel to the layering are seen both inside and on the surface of the split core within the block, but not in the lower part within the original seabed. This might possibly be an indication of internal disturbance as the block slid downslope and stopped.

The sea floor sediments below the block have been compacted by the weight of the block, which has increased the undrained shear strength. Nonloaded
sediments from the adjacent seabed surface will show significantly lower undrained shear strength than the material underneath the block (Fig. 2). Information from other cores outside the debris flow area reveals low shear strengths and high water contents in the upper part of the sampled sediment sequence. Typically, undrained shear strength is in the range of 0.5–6 kPa in the upper 10 cm of bed sediments.

3. Experimental study

A set of subaqueous debris flow experiments was carried out in the facilities of St. Anthony Falls Laboratory, University of Minnesota, in order to investigate frontal dynamics and morphology of submarine debris flows. These experiments represent a continuation of previous work in both confined and unconfined settings, which has been the source of new insights into the flow dynamics of subaqueous clay-rich mass flows (Mohrig et al., 1998, 1999; Marr et al., 2001; Ilstad et al., 2004). The present experiments were performed in a 2.25-m-wide and 9.0-m-long slope inside a larger long channel (see Fig. 3). The head tank was loaded with 680 kg of premixed sediment, which was released through a gate. The sediment was composed of clay minerals (kaolin) and sand (mean grain size, 330 μm) and was mixed with water in a mortar mixer for approximately 1 h; it thus represented completely remoulded sediment.

When placed in the head tank, the sediment was fully submerged at the start of the experiment, covered by a few centimeters of water. The sliding sediments, forming typical debris flows, ran down an 8° slope over a hard, granular-coated bed designed to ensure no-slip bed friction for sediments in contact with the bed. Experiments were recorded by several video cameras during the flow event and depositional features were recorded with photos and video.

When sufficient speed is obtained, a dynamic pressure under the debris head (Mohrig et al., 1998) combined with a suction on top (Hampton, 1972) lifts the front, and water penetrates beneath, leading to hydroplaning of the frontal part. The decreased bed friction at the front compared to that of the following masses creates tension in a zone behind the front. The resulting stretching may cause detachment of the front from the main body, creating an outrunner block. The block is then free to move downslope without any influence from the main sliding masses behind.

Immediately after the head gate has been opened, the sediments accelerate (Fig. 4) and spread out both laterally and down the slope (Fig. 5A). From the point where the front starts to hydroplane (Figs. 5B and 6B), a different spreading pattern is observed. Lateral spreading diminishes in the hydroplaning part and the front itself moves more like a coherent lobe (Fig. 5B–D). As the hydroplaning lobe moves downslope (Fig. 6B–D), a necking area starts to develop between the hydroplaning and the nonhydroplaning parts (Fig. 5D), revealing the initiation of the detachment phase. The front is torn away from the main body of the slide in the necking area (Fig. 5E). An outrunner block is formed and glides above the bed with greatly reduced bed friction (Figs. 5F and 6F).

The downslope movement of the block is controlled by driving forces (gravity) and resisting forces (viscous drag and bed interaction). After initiation of

Fig. 3. Experimental slide facility. Sediments are filled in the head box and released through the front gate.
hydroplaning, an increase in speed further increases the front pressure. This produces increased lift of the front, causing an upward flipping. The increased drag from this uplift results in a decrease in speed (Fig. 4). Two different behaviours are observed in the experiments: the front may settle down close to the bed again; alternatively, the front may flip back on top of the masses behind, forming a new, thicker front (Fig. 6E and F). Front flipping is seen all along the flow path, but is most prominent during and just after block formation. Small upward flipping of the front causes the speed to oscillate during the flow.

The overall depositional pattern (Fig. 7) is classified in the same manner as for the field observation. The main lobe forms a well-defined body 1.5 m outside the head gate (zone A in Fig. 7).

Fig. 4. Front velocity in the initial phase after release of slide with reference to pictures in Figs. 5 and 6. Front speed is reduced due to flipping from 120 to 160 cm.
Scattered blocks are found in zone B from about 1.5 to 2.5 m. In zone C, from 2.5 to 7.5 m, small deposits are found along the glide path of the outrunner block.

Undulation of the bed surface may also lead to bed contact that erodes sediments from the basal surface of the block. Orientation of deposited blocks is, to some degree, arbitrary since the impact and scraping with the bed often cause the block to rotate during deposition. The outrunner block was deposited around 8 m downslope, rotated approximately 45° relative to its orientation during motion (zone D, Fig. 7). When the outrunner block reaches the end of the slope, marked by an abrupt change in slope, it stops rather quickly. This sudden stop may lead to some rotation and subsequent deformation, depending on which part of the block first touches the bed.

The block may scrape or bump into the bed during flow, leaving a trail of fragments of sediment on the rough bed. Videos show that one or both side tips experience full contact with the bed, and are gradually torn off the block, leaving oblong patches of sediment along the edges of the glide track (Fig. 8C–E). It is suggested that the block may scrape the bed due to the reduced lift at the tips. Vertical cracks in the front and

Fig. 6. Snapshots (subaqueous camera) of flipping of the front. Spacing in the grid is 20×20 cm. (A)–(C) show the initial phase where the front starts to bend or flip upwards. (D) and (E) show the front flipping backwards. (F) shows the new front formed by the front flipping backwards and folding on top of the body behind.

Fig. 7. (I) Depositional features in experimental debris flow with outrunner blocks. Slide morphology is divided into zones comparable to zones in Fig. 1. (A) Main lobe. (B) Zone with scattered blocks. (C) Glide zone. (D) Main outrunner block. (II) Depositional features (shaded) from outrunners.
sides of the block are attributed to lateral strain induced by the increased friction when the sides scrape along the bed; this may cause further break-up of the block (Fig. 8E).

4. Relations between experiments and field

The scale of the experiment compared to the Finneidfjord slide is approximately 1:200 in the horizontal direction. Although these slides have been operating on a quite different scale, noticeable resemblance in depositional patterns is found. The experiments suggest that similar depositional processes are at work in both the field and the laboratory. We propose that laboratory flow experiments may provide valuable insights into the dynamics and depositional processes of outrunner blocks.

At both scales, the main slide body has moved a finite distance, forming a well-defined body, zone A (Figs. 1 and 7 for the field and the laboratory, respectively), followed by a zone B with scattered blocks. This is the termination area of outrunner blocks that, despite a short runout, must have been subjected to some lubrication since they detached from the main lobe. A glide track zone, C, stretches from the scattered blocks to the outrunner block. A wide spread of small blocks is found in this zone. On the assumption that the experiments may be used to interpret the flow behaviour, and by their proximity to the glide track, it is believed that these small blocks in the Finneidfjord slide have been torn from the larger outrunner block. At the end of the track, the large block, D, is found. In both cases, it has stopped due to a marked change in bottom slope, which terminated the driving force (downslope gravity pull).

In contrast to outrunner blocks in Finneidfjord, which are much smaller in size than the debris flow, pull-apart blocks in the experiments have a width approximately comparable to the originating debris flow. This may be due to the fact that the Finneidfjord slide developed in several stages and not as a single slide event, and to the fact that a very smooth seabed must be present from the pull-apart area and downslope in order to preserve a very wide outrunner block.

Fig. 8. Depositional process by outrunner blocks. (A) – (E) show the sequence of detachment resulting in oblong patches of material left along the edges of the glide. Frictional bed contact at the edges causes strains at the front, leading to possible cracking (E).
5. Theory

The scope of the theoretical study is to understand the frontal dynamics of submarine debris flows and, more quantitatively, the generation and flow of outrunner blocks (Fig. 9) as a function of the material strength. Derived estimates are checked against experimental data and extrapolated to the field. The basic argument maintained in this section is that outrunner blocks are lubricated underneath by a thin water layer or by soft seabed sediments during flow. The lubrication reduces basal shear stresses and increases the runout length of the blocks.

5.1. Hydroplaning of debris flows

As the front pushes its way through water with speed $U$, the frontal pressure is approximated by the stagnation pressure:

$$P_f = \frac{1}{2}\rho_w U^2$$

where $\rho_w$ is the density of water. At fully developed hydroplaning, the lubricating layer must support the submerged average load per unit area from the block $\Delta p g H \cos \beta$, where $\Delta p$, $g$, $H$, and $\beta$ are the density difference between sediment and water, acceleration of gravity, block height, and slope angle, respectively. These pressures form the basis of the densimetric Froude number $Fr$, which has been used by several authors in the scaling of the dynamic pressure on a moving body (Mohrig et al., 1998; Harbitz et al., 2003):

$$Fr = \frac{U}{\sqrt{\frac{\Delta \rho}{\rho_w} g H \cos \beta}}$$

A value for $Fr$ between 0.3 and 0.4 is reported (Mohrig et al., 1998) to constrain the onset of hydroplaning, but during flow once hydroplaning is established, values in the range of 0.8–1.4 are found (Ilstad et al., 2004). Frontal pressure may deform the head, increasing the lift of the snout in combination with the reduced pressure above the head (Hampton, 1972). This may explain the fact that hydroplaning occurs when front pressure is less than the average load from the block (Froude number less than $\sqrt{2}$).

Fig. 9. (A) Formation of an outrunner block from the front of a hydroplaning debris flow. A block is torn off the front and glides ahead in front of the main body of the debris flow. (B) Stresses and forces acting on the outrunner block.
In field cases, undulation of the seabed may lift the front of the bed, thus allowing for water to penetrate underneath the front.

5.2. Formation of an outrunner block

In order for an outrunner block to be generated, the tensile stress between the lubricated and nonlubricated parts of the debris flow must exceed the tensile strength of the material (Hampton, 1970), which suggests a simple criterion for the detachment. Based on Fig. 9, one finds the tensile stress, \( \sigma_t \), in the cross section between the lubricated and nonlubricated parts by integrating the stresses in the \( x \)-direction from the front:

\[
\sigma_t = C_p P_L + \left( \frac{1}{H} (\bar{\tau}_\text{lub} + \bar{\tau}_\text{top}) - (\Delta \rho g \sin \beta - pa) \right) L,
\]

where \( \bar{\tau}_\text{lub} \) is the mean shear stress experienced underneath the lubricated block, \( \bar{\tau}_\text{top} \) is the mean shear stress on top of the lubricated block, \( L \) is the length of the block, \( \rho \) is the sediment density, \( a \) is the acceleration, and \( C_p \) is the pressure drag coefficient for the front.

For a clay material, the limiting tensile stress for detachment to occur is given by \( \sigma_{t,\text{limit}} = -2s_u \), where \( s_u \). By using Eq. (2), one thus finds that the length of the block depends on the material strength, geometry, and slope inclination as:

\[
L = \frac{4s_u + C_p Fr^2 \Delta \rho g H \cos \beta}{2(\Delta \rho g \sin \beta - pa) - \frac{2}{H} (\bar{\tau}_\text{lub} + \bar{\tau}_\text{top})} \quad \text{Fr}>0.3
\]

The first term in the numerator is related to the material strength, \( s_u \), and shows that an increase in strength will increase the block length linearly. The block length is also dependent on the slope angle \( \beta \) (especially in the denominator of Eq. (4)) and small changes in the slope angle may have a large influence on the block length.

Assuming negligible acceleration, the calculation above gives a block length of about 30 cm for the experimental outrunner block, using an undrained shear strength of 150 Pa and values from Table 1. Looking at Fig. 5E, the actual length of the block is estimated to be about 35 cm. Considering the approximations, this agreement is satisfactory. Fig. 6 reveals that the front of the debris flow, which later becomes fragmented and is deposited as pull-apart blocks, acquires considerable lubrication due to hydroplaning.

We now apply Eq. (4) to Finneidfjord. Considering a normally consolidated sediment package, and assuming that the outrunner block is generated from the surface sediments with no remolding, then a rough estimate of the mean undrained shear strength

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<th>Table 1</th>
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<td>Model input for the calculation of runout of blocks. Drag coefficients and viscosities from Newman (1977), assuming a Reynolds number of ( 3.2 \times 10^3 ) in the experiment and ( 2.7 \times 10^7 ) for the Finneidfjord case and using the thickness-to-length ratios of the blocks</td>
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<td>Mean shear strength, block (Pa)</td>
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for block heights of 2–20 m would be in the range of 5–50 kPa. The slope angle has to be calculated in the detachment area of the runout path, where the slope inclination most likely is higher than in the area where the block ceases to move and stops. Outrunner blocks are formed in muddy environment in fjords and on continental slopes (Booth et al., 1993) with slope angles often less than 5°. Fig. 10 shows calculated block lengths using the above assumptions. Fixing a shear strength on the order of 10 kPa (Fig. 2) and a slope angle of 2.86°, the calculated block length is about 60 m, which is also of the correct order compared to field observations. The fact that a consistent value is recovered is important in assessing the role of hydroplaning in Finneidfjord. If the front of the debris flow is not lubricated, then $\tau_{\text{lub}}$ has to be substituted by $s_u$ in Eq. (4), and the second term of the denominator is no longer negligible. The length of the blocks might then become comparable to, or longer than, the size of the debris flow, which would then mean that the debris flow flowed as a single body without fragmentation and formation of blocks.

The larger slope inclination in the part of the fjord where the debris flow was initiated might also have provided the high velocity that enabled the block to become detached at the slope break. In general, a large-sized debris flow moves faster than a small one because the gravity pull increases with the mass, while the resistive forces increase with the surface of the debris flow. The debris flow acquires high velocity by travelling together, thus giving the block a high initial velocity, which would help the blocks travelling at smaller slope inclinations.

5.3. Front flipping

As previously discussed, in the experiments, upward flipping of the front of outrunner blocks was observed during the flow (Fig. 6). Two different kinds of behaviour occurred as a result of flipping. The increased drag sometime resulted in a decrease in speed, allowing the front to settle down close to the bed again. This produces a quasi-periodical behaviour. Alternatively, the front may flip back on top of the masses behind, forming a new and thicker front (Fig. 11D–F). As the velocity of the block increases, the pressure underneath the block will also increase. When the pressure over a substantial length behind the front of the block equals the submerged weight per unit area, any further increase in speed
may destabilise the front. The pressure underneath the flipping front of length $L_{\text{flip}}$ with flipping angle $\theta$ applies a torque (per unit width), $M_{\text{flip}}$, around the rear end:

$$M_{\text{flip}} = \frac{1}{2} (L_{\text{flip}})^2 \left( \frac{1}{2} \rho_w U^2 - \Delta \rho g H \cos(\theta - \beta) \right)$$

assuming stagnation pressure underneath the whole flipping front. This is represented by the first term on the right-hand side, while the second term is the gravity pull. Resistance to flipping is governed by gravity and the strength of the block. When the flip torque reaches the torque capacity of the block, $1/2\,s_u H^2$, flipping is initiated and the velocity, $U_{\text{flip}}$, becomes:

$$U_{\text{flip}} = \sqrt{\frac{2}{\rho_w} \left( s_u \left( \frac{H}{L_{\text{flip}}} \right)^2 + \Delta \rho g H \cos(\theta - \beta) \right)}.$$  

(6)

Flipping lengths of about $L/4$ to $L/3$ are observed in the experiments. When the front begins to flip upward, it creates a larger front area, which has to displace more water at the front (Fig. 11A–D). The drag thus increases and produces a decrease in velocity. At the end of the back-flipping process, the front area is reduced (Fig. 11E and F) and the velocity will once again increase. The front height changes with the flipping angle, $\theta$, as:

$$H_{\text{front}} = H \cos \theta + L_{\text{flip}} \sin \theta$$

(7)

thus changing the front drag during flipping. When the forces acting on the debris flow are ideally in equilibrium and the slope is constant, the velocity, $U_{\text{lim}}$, of a nonflipping block remains constant, equal to:

$$U_{\text{lim}} \approx \sqrt{\frac{2 \Delta \rho \rho g \sin \beta}{\rho_w \left( \frac{C_p}{T} + \frac{C_f}{H} \right)}}$$

(8)

where $C_p$ and $C_f$ are the pressure and skin friction coefficients, respectively (Table 1). In the geometrical setting of the laboratory flow, the ratio $C_p/L$ is significant. Hence, the backwards flipping tends to slightly increase the drag and reduce the velocity (Fig. 13).

5.4. Critical velocities and shear strength for the block to remain intact

In order for the front to remain intact and not break apart or disintegrate during the travel downslope, it must resist the dynamic stresses all along the path. From experiments, it is seen that the greatest erosion is at the head, as a result of the dynamic pressure and shear at the front. The strength of the block must at least resist these effects. A simplified calculation of the front stability, based on classical Rankine earth pressure zones commonly used in soil mechanics, gives a maximum dynamic front pressure for a given shear strength of the block. We assume undrained conditions for the clay material in the front and apply a Tresca failure criterion, with $s_u$ as the undrained shear strength. Fig. 12 shows the Earth pressure zones. Neglecting the shear stresses at the front, one finds:

$$P_{\text{f}} = \frac{1}{2} \rho_w U^2 = 2(1 + \omega) s_u \quad 0 \leq \omega \leq \frac{\pi}{4}$$

(9)

where $\omega$ is the angular extent of the middle Rankine zone. It is seen that a vertical front ($\omega=0$) supports the lowest front pressure, while reshaping the front will allow for higher front pressure. A vertical front may be...
sustained at low velocities but higher velocities reshape the front until stability is found. The maximum speed before break-up of the front is found from Eq. (9):

\[ U < \sqrt{\frac{4(1 + \omega) s_u}{\rho_w}} \]

(10)

A classification of front behaviour based on the dimensionless yield stress, \( \tilde{\tau}_y = \tau_y / \rho_w \), has been proposed (Mohrig and Marr, 2003; Ilstad et al., 2004) based on debris flow experiments where highly cohesive fronts and outrunner blocks are observed for values higher than 0.25. Based on Eq. (1) and experimental observations, this gives, by rearrangement and replacing \( \tau_y \) with \( s_u \), a maximum front speed of:

\[ U < \sqrt{\frac{8s_u}{\rho_w}} \]

(11)

which is of the same order as the simplified calculation (Eq. (10)). Combining Eq. (10) with Eq. (2), one finds that the minimum shear strength needed for a hydroplaning block of a given height to remain intact is:

\[ s_u > \frac{Fr^2 \Delta \rho g H \cos \beta}{4(1 + \omega)} \quad \land \quad Fr > 0.3 \quad \land \quad 0 \leq \omega \leq \frac{\pi}{4} \]

(12)

6. Simulation of outrunner block in the experiment and Finneidfjord

A simple model for the motion and runout of the outrunner blocks is suggested, based on the force balance on the block. The dynamical equation for the block is:

\[ \rho_s V_{\text{block}} a_{\text{block}} = F_{\text{grav}} - F_{\text{drag}} - F_b \]

(13)

where \( F_{\text{grav}}, F_{\text{drag}}, \) and \( F_b \) are the gravity, drag, and basal forces; \( V_{\text{block}} \) is the block volume; and \( a_{\text{block}} \) is the block acceleration. The forces are written as follows:

\[ F_{\text{grav}} = \Delta \rho g V_{\text{block}} \]

(14)

\[ F_{\text{drag}} = \frac{1}{2} \rho_w (V_{\text{block}})^2 (C_p A_{\text{front}} + C_t A_{\text{top}}) \]

(15)

\[ F_b = \tau_b A_b, \tau_b \]

\[ = \left\{ \begin{array}{ll} \mu_w \frac{U}{t_w} & \text{for } U \geq Fr \sqrt{\frac{\Delta \rho g H \cos \beta}{\rho_w}} \\ \tau_y + \mu_s \frac{U}{l} & \text{for } U \geq Fr \sqrt{\frac{\Delta \rho g H \cos \beta}{\rho_w}} \end{array} \right. \]

(16)

where \( A_{\text{front}} \) and \( A_{\text{top}} \) are the areas of the outrunner block, respectively, seen from the front and from above; \( t_w \) and \( \mu_w \) is the thickness and viscosity of the water layer, respectively; and \( t_s \) and \( \mu_s \) is the thickness and viscosity of the seabed shear layer, respectively (with thickness different from zero only in the absence of lubrication). The equation for the angular acceleration of the flipping front reads:

\[ \frac{1}{2} \rho_s V_{\text{flip}} L_{\text{flip}} \ddot{\theta} = \left( M_{\text{flip}} \pm s_u \frac{H^2}{2} \right) W \]

(17)

where \( \ddot{\theta} \) is the angular acceleration, \( V_{\text{flip}} \) is the volume of the flipping front, \( W \) is the block width, and the flipping moment per unit width, \( M_{\text{flip}} \), is given in Eq. (5).
The model gives the response of the block to the gravitational pull determined by the slope angle and the resistive forces derived previously. It is assumed that the hydroplaning block has formed and is free to move downslope. Maximum velocity is limited by slope angle and flipping. The slope angle determines the available gravitational pull and flipping starts when a critical speed is reached. For velocities lower than the initiation of hydroplaning, the block is assumed to have full bed contact.

This allows for backcalculation of the outrunner block in Finneidfjord and in the experiments, using the model input data in Table 1. Fig. 13 shows velocities and flipping angle during the runout for both the experimental and the Finneidfjord outrunner blocks. The model velocity shows a resemblance to the measured values for the experimental outrunner block (Figs. 4 and 13A). Flipping occurs in both the model and the experiment. After backward flipping, a new configuration of the block is found, with an increased height and decreased length. In the experiment, the block flows farther downslope and flips slightly again before the velocity becomes constant, indicating an equilibrium situation between the drag and the downslope gravitational force.

The Finneidfjord block is assumed to have been generated in the outermost area of zone A, Fig. 1, and the bed profile along the glide path is found from the swath bathymetry. From the generation area with a slope angle of 2.86°, it ran into a 150-m-long slope of 0.94° before reaching the fjord bottom with a slope of 0.46°. The analysis shows that the block was accelerated in the first part with the highest slope angle, before it reached the fjord bottom, decelerated, and attained a steady velocity. Assuming that the block was generated 46 m above the first slope break, the block flipped slightly just before reaching the fjord bottom. Generation of the block above this point would have led to flipping, while blocks generated below this point would have shown no flipping.

Based on the existing data, it is most likely that the block did not flip backwards. Support for this idea comes from the sediment core, which does not show repeated layering. Fig. 13B shows the runout for a block, which flips slightly before reaching the fjord bottom (solid line) and a block flowing without flipping (dashed line); the latter started some distance downslope of the flipping block, thus giving the block less potential energy. The flipping block is subject to a higher drag during flipping and enters the fjord bottom with less speed than the nonflipping block. Both blocks decelerate and reach a steady velocity of 4.5 m/s at some distance along the fjord bottom.

Fig. 13. Modelling of outrunner blocks. The upper panels show velocities and bed elevations, and the lower panels show flipping angles along the runout path. (A) Experimental outrunner block. Velocities may be compared to measured velocities in Fig. 4. (B) Finneidfjord outrunner block. Solid line shows the velocity of a block flipping slightly, thus representing the highest generation point in the slope for a block to stay intact when reaching the low-angle fjord bottom. Dashed line shows a block that is not flipping. This block is generated a small distance further downslope than the first block, giving it less potential energy.
7. Discussion and concluding remarks

The behaviour of the frontal part of a debris flow can affect the dynamics of the whole body. Processes such as hydroplaning and the generation of turbidity currents are governed by the frontal dynamics. This may alter the further dynamics of the debris flow in a radical way. A better understanding of the frontal dynamics may be developed from analysing outrunner blocks detaching from the front of some highly cohesive debris flows. Outrunner blocks also represent an important problem per se, as they may outrun the debris flow by tens of kilometres.

In this article, we presented field data, laboratory experiments, and theoretical studies of the front of submarine debris flows, with particular emphasis on the generation and flow of outrunner blocks.

Due to the limited dimensions of the debris flow, the modest water depth, and the site’s accessibility, the information available for Finneidfjord is of high quality. In order to seek insight into the processes occurring during the formation (Fig. 14A and B) and flow of outrunner blocks (Fig. 14C), debris flows were generated in a laboratory tank. The conditions that are found to be essential to the formation and flow of experimental outrunner blocks can be summarized as follows: (1) the material must be sufficiently strong and rigid (which implies that clay content must be sufficiently high); and (2) it must be lubricated at the base. In the laboratory, the lubrication is due to hydroplaning, which occurs if the blocks move sufficiently fast such that the pressure build-up in front of the debris flow lifts the head off the seabed, and allows for intrusion of a water layer underneath the head.

We argue that these conditions must also be met in the field for the outrunner blocks to be formed. An essential argument for this is based on the very similar depositional morphology between the laboratory experiments and the field. Thus, we suggest that the morphology and processes observed in the laboratory are also applicable to the field.

A criterion that provides a lower limit for the strength of the material in Finneidfjord is that the shear strength must be higher than the disruptive shear stresses that may otherwise cause the front of the debris flow to disintegrate. Values extracted in this way give a lower limit for the undrained shear strength, which is compatible with the values found with rheological tests on the material. In our experiments, a large initial acceleration of the debris flow is ensured by providing a high potential energy to the slurry, via a large initial thickness and steep slope. The acceleration phase in Finneidfjord was also probably important, gaining the speed needed for hydroplaning.

We find that the lengths of blocks are mainly dependent on the material strength and slope angle in the generation area. Lengths and widths of blocks found on the continental slope (Nissen et al., 1999; Kuijpers et al., 2001) are within the same order of magnitude as in Finneidfjord, which may suggest an upper limit on the size of outrunner blocks.

Comparison of velocities of a simplified flow model and laboratory experiments of outrunner blocks

Fig. 14. (A) Detachment phase with lubricating front. (B) Outrunner block is formed and flows away from the main slide. (C) Hydroplaning block leaving a faintly visible track with linear patches of sediment along the track edges.
shows reasonable agreement indicating that the main behaviour is captured in the model. These simplified calculations also show that the outrunner block in Finneidfjord would have continued further out through the fjord, possibly for several kilometres, if it had not come to rest on the rising slope of the moraine ridge.

Focusing on the outer distal part of the slide, we suggest a division of the slide morphology into four zones (Fig. 15), based on depositions in field and from laboratory experiments. The main features in the depositional pattern of experiments and field seem to be similar, and thus the depositional processes are likely to be comparable.

Although this work focused on the Finneidfjord case study, some of the results presented here can possibly be extrapolated to other cases. Table 2 presents a collection of observational field data concerning deposition of outrunner blocks. Prior et al. (1982) reported the presence of outrunner blocks of 50,000 m$^3$ and 1 km runout from a landslide that occurred in 1975 in the Kitimat area in Canada. The soil was disturbed by the passage of the block as revealed by high-resolution sonar, and glide tracks that were much deeper than those in Finneidfjord were detected. Nissen et al. (1999) described outrunner blocks on the Nigerian continental slope, where glide tracks reach an exceptionally long runout of 12 km and a depth of 5–10 m, on a slope of only 1–1.4°. Kuijpers et al. (2001) describe glide tracks and outrunner blocks on the Faroe margin. Groove depths of up to 4 m were detected and block runouts reach the stunning distance of 25 km. In these reported case studies, the blocks are much larger than in Finneidfjord and the grooves are correspondingly deeper and wider.

To conclude, we have applied joint experimental and theoretical investigations to assess frontal dynamics and especially the formation and motion of outrunner blocks in Finneidfjord, showing that the laboratory and field morphologies are comparable. The most fundamental part seems to be that, due to hydroplaning, tensile stresses lead to the formation of outrunner blocks. Dimensions of the outrunner blocks are related to the material strength. These outrunner blocks show a higher mobility than the main slide body and deposits may occur far beyond the main slide body.

<table>
<thead>
<tr>
<th>Slide (and setting)</th>
<th>Nigeria (continental slope)</th>
<th>Kitimat, Canada, 1975 (fjord)</th>
<th>Faeroe margin (continental slope)</th>
<th>Finneidfjord, Norway, 1996 (fjord)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratigraphic setting</td>
<td>Subsurface, 144 ms below seafloor</td>
<td>Surface</td>
<td>Surface</td>
<td>Surface</td>
</tr>
<tr>
<td>Dimension of the blocks, $L \times W \times H$ (m)</td>
<td>$100 \times 250 \times 10$</td>
<td>$75 \times 125 \times 2-5$</td>
<td>$70 \times 100 \times 18$</td>
<td>$60 \times 110 \times 2$</td>
</tr>
<tr>
<td>Slope (°)</td>
<td>1 to 1.4</td>
<td>0.37</td>
<td>0.6</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Acknowledgements

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