

Controls of the behavior of marine debris flows

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A two-dimensional layer-averaged Bingham fluid numerical model has been used to explore the relative importance of yield stress, kinematic viscosity, bottom slope and initial failure height on the run-out distance of debris flows. The parameter ranges used include low values that are appropriate to marine conditions where debris flows can travel large distances on very low slopes. The sensitivity analyses demonstrate that the yield stress exercises much more control than the viscosity, especially within the value ranges that are often used to simulate the formation of marine debris flow deposits. In practice, low values of the Bingham fluid parameters are used in numerical simulations of observed deposits to compensate for a number of detailed flow phenomena that are not included in the model. These processes are described, and recommendations are made for including them in future models.

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Introduction

Marine mass gravity flows in general, and a subclass called debris flows, have become of increasing interest to engineers designing deep water installations and geologists seeking to understand the deposits formed on, and below, the continental slope. In this paper we summarize the emerging understanding of the nature and characteristics of marine debris flows and dynamically similar mudflows. Our purpose is to provide guidance to studies that include field measurement programs and quantitative analyses of these flows. To this end, we show how the flow kinematics vary according to mode of origin, flow path characteristics and material properties. Not all of the flow characteristics are quantitatively evaluated because, at this time, the conceptual understanding is developing faster than our ability to model it.

Background

Mass gravity flows consist of more or less rapid movement of fluid sediment masses that are driven downslope by gravity. Marine debris flows are a subclass. The terminology used in different fields (e.g. marine geology, ocean engineering, stratigraphy) is not clear (Elverhøi et al. 2000; Elverhøi et al. 2005; Niedoroda et al. 2000; Reed et al. 2000; Gani 2004). The basic categories are turbidity currents, debris (and mudflows), and grain flows. Gani (2004) recognizes that these flows are distinguished by four characteristics: sediment concentration, sediment-support mechanism, flow rate, and

rheology. Of these, rheology is the most diagnostic. Debris flows have relatively high sediment concentrations and generally behave as non-Newtonian fluids. Most of these flows are formed from gravitational slope or soil mass failures.

Four stages of debris flow events are commonly identified: initial failure (trigger event), transition, flow, and deposition. During the transitional stage as the soil mass accelerates and remolds, its internal particle-to-particle structure is deranged and its strength drops. Strength decreases by factors of two to three are common (Locat & Lee 2002) and in extreme cases may be an order of magnitude or more (Locat & Demers 1988). Submarine events also have an opportunity to uptake water.

Behavior during the flow stage largely depends on the composition of a debris flow. This is determined by the relative amount of cohesive clay and granular particles, the size of the grains and clasts, the clay mineralogy and the water content (Middleton & Hampton 1973, Marr et al. 2002; Ilstad et al. 2004c; Elverhøi et al. 2005). In coarse-grained debris flows where the clay content is relatively low, the flow is characterized by both an internal shearing and grain-to-grain dispersive pressures (Huang & García 1998). However, in our experience the most common marine debris flows are not coarse-grained, have considerable clay content (> 25 %) and deform plastically in a manner that is reasonably described as Herschel-Bulkley or Bingham non-Newtonian fluids (Marr et al. 2002; Elverhøi et al. 2005).

Debris flows and mudflows occur in both terrestrial

and submarine environments. It has been noted that remobilization of an antecedent deposit by a subsequent subaerial debris flow is common, but this need not be the case for submarine events (Mohrig et al. 1999). Submarine mud and debris flows can have much larger run-out distances on low slopes than their subaerial equivalents (De Blasio et al. 2004; Ilstad et al. 2004a, 2004b; Harbitz et al. 2003; Elverhøi et al. 2005; Elverhøi et al. 2000). This behavior is somewhat counter intuitive because submarine flows have their driving force reduced by buoyancy and witness a higher total hydrodynamic drag than subaerial flows. Nevertheless, submarine debris flows have been shown to travel 10s and even 100s of kilometers on slopes of less than two degrees (Prior et al. 1984; Issler et al. 2003; Elverhøi et al. 2000, 2005; Mohrig et al. 1999; Marr et al. 2002).

There appear to be a number of phenomena that account for the very mobile behavior of submarine debris flows. Prior et al. (1984) attributed the long run-out distance of a debris flow in Kitimat Fjord to weak underlying sediments. Investigations of the Storegga debris flow and the smaller flow in the Ormen Lange area off Norway have concluded that there are progressive changes in material properties of the mud as it travels. De Blasio et al. (2003) modeled the Storegga debris flow and found that the Bingham yield stress probably decreased with distance traveled because no single value would produce the correct thicknesses over the whole length of the resulting deposit. De Blasio et al. (2004) noted that large undeformed blocks were incorporated in the Storegga debris flow. They proposed that these moved great distances along with the surrounding debris flow because they were supported on a lubricating layer. This layer was originally a weak layer in the initial soil mass, whose failure triggered the flow. They proposed that the soles of the huge blocks were coated with this weak clay, which provided the lubrication to move them. Elverhøi et al. (2005) and De Blasio et al. (2005) describe shear-wetting (or strain-induced wetting) as a mechanism wherein ambient water enters the debris flow from above as it travels.

In addition to these mechanisms, considerable attention has been given to a phenomenon where the head of a debris flow hydroplanes in much the same way that vehicle tires lose direct contact with a wet pavement. Mohrig et al. (1998) introduced this concept supported by scale model data. They showed that the onset of hydroplaning in the experiments was related to a threshold value of the densimetric Froude number. At least two conditions are needed for the head of a debris flow to hydroplane. Mohrig et al. (1999) showed that, in addition to accelerating to the speed needed to satisfy the threshold Froude number, the debris flow needs to be clay-rich so that it remains a coherent fluid mass as it flows. Elverhøi et al. (2005) define a clay-rich mud-

flow as more than 25 percent clay. They found that weakly coherent "sandy" debris flows have less than 10 percent clay and moderately coherent flows have 10-20 percent clay. Mohrig & Marr (2003) and Ilstad et al. (2004c) point out that sandy debris flows lack the coherence needed to hydroplane. Instead, when they accelerate, the heads tend to take on ambient water, expand and become turbulent. This is a direct transition to a turbidity current.

Ilstad et al. (2004b) made pore pressure measurements beneath scale model debris flows and showed that the excess pore pressure in the water layer trapped by the hydroplaning dissipates slowly. Thus the lubricating layer can persist far behind the head of the debris flow. In addition to accounting for the long run-outs of debris flows on very small slopes, the hydroplaning of the heads of clay-rich debris flows may explain some of the outlier blocks such as those noted by Prior et al. (1984) in the Kitimat Fjord. Ilstad et al. (2004a) introduce the concept of "auto-acephalation." The wedge of water beneath the head of the rapidly flowing mud can locally reduce the friction to the point that the head outruns the rest of the debris flow.

Engineers and scientists faced with evaluating the hazard posed to planned deep-water seafloor structures (pipelines, wells, manifolds, etc.) have benefited from these research developments. These applications usually have the dual purpose of developing an understanding of how observed debris flows formed and then using this understanding to predict the likely behavior of future events that could threaten the facilities.

Guidance for selecting the non-Newtonian fluid parameters to properly model observed debris flows comes from a number of studies. Both Issler et al. (2003) and Issler et al. (2005) examined the data from the Storegga slide measurements and showed that the run-out distance and the ratio between fall height and run-out distance are described by a power-law function of the debris flow volume. Marr et al. (2002) used the BING model and bottom profiles from the Isfjorden Fan and Bear Island debris flows to evaluate the sensitivity of the run-out distances to the fall height, volume and fluid parameters.

For the Isfjorden Fan simulations four yield strengths in the range of 10- – 25 kPa and two viscosities (30 and 300 m²/s) were input. A single volume and the same curved bottom profile were used for all runs. The results show that yield stress provided the dominant control of the run-out distance. The dynamic viscosity had a small effect on the computed deposit thickness and only provided an observable influence on the run-out distance at the lowest yield stress. This is in agreement with the results of laboratory soil testing reported in Locat & Lee (2002) that the yield stress contributed

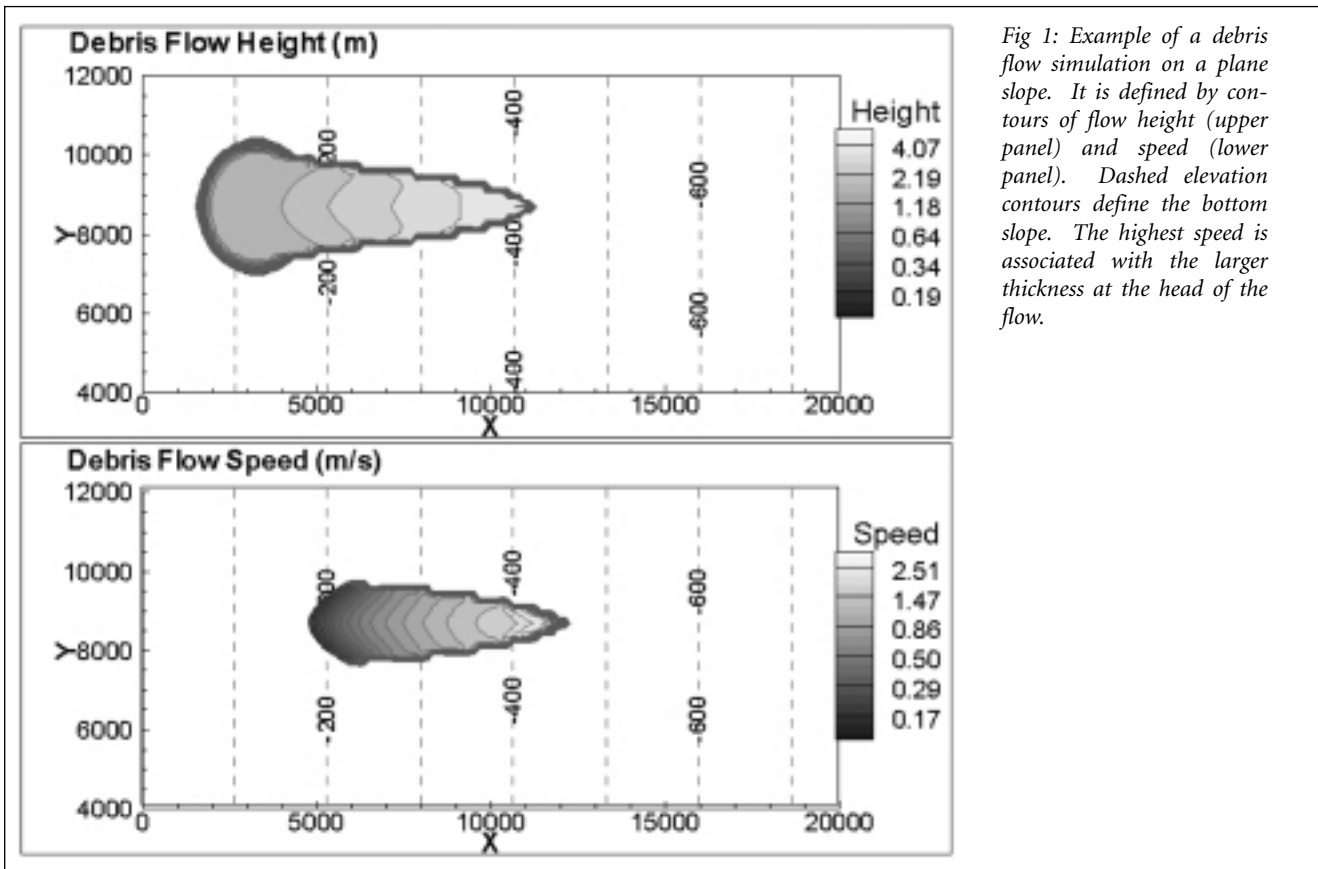


Fig 1: Example of a debris flow simulation on a plane slope. It is defined by contours of flow height (upper panel) and speed (lower panel). Dashed elevation contours define the bottom slope. The highest speed is associated with the larger thickness at the head of the flow.

in excess of 1000 times more to the flow resistance of a mud than the viscosity. In the Bear Island simulations Marr et al. (2002) used yield strengths in the range of 1–5 kPa and the same two viscosities as in the Isfjorden Fan runs. Also, as in the previous case, single curved bottom profile and flow volumes were used. The results were generally the same, but because they were using a lower range of yield stress, the effect of viscosity on the run-out distance was more pronounced.

Elverhøi et al. (2005) used two versions of the BING model to explore the effect of hydroplaning on the debris flow run-out distance. In addition to the basic model the second version, named Water-Bing (or W-BING), had been modified to include the effect of hydroplaning. Their results showed that hydroplaning increased the run-out distance on the order of three to five times the distance predicted by the models for non-hydroplaning conditions over a range of yield stress values between 3 and 15 kPa. They attributed the marked increase in run-out distance predicted by W-BING for the lower yield stresses to a tendency for these flows to hydroplane earlier than the stiffer flows. While hydroplaning conditions are maintained, the resistance in the lubricating layer controls the run-out much more than the effects of the yield stress.

Approach

A numerical model was used to explore the dependence of run-out behavior on the controlling geometric and fluid variables. The range used is broad so that the model can mimic most of the previously described flow behaviors.

The numerical model

The DM-2D mudflow/debris flow model has been explained in Niedoroda et al. (2003). It is an Eulerian gridded model based on the thin layer approximation to the Navier-Stokes and mass continuity equations. The model assumes that the flow is thin (relative to its length) and that its rheology can be represented as a Bingham fluid.

The bottom stress is determined from the flow kinematics. The model assumes that the flow consists of an un-deformed and a deforming layer. The un-deformed layer is the region in which the shear stress is below the yield strength. This layer extends from the upper surface to a critical depth that is calculated each time-step based on the local slopes of both the upper and lower flow boundaries. In the lower region, the mud is assumed to be a viscous fluid with a parabolic velocity profile that extends from the bed to the base of the un-

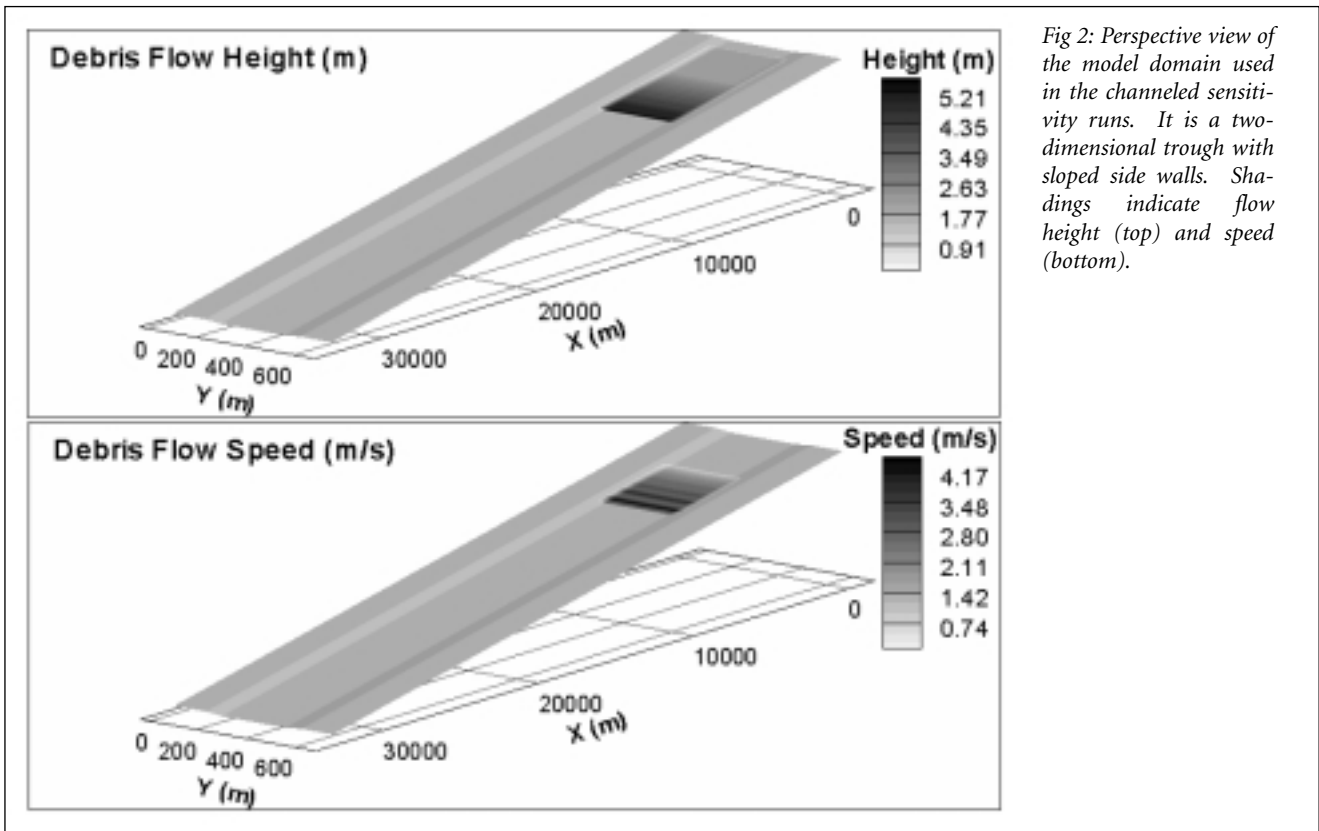


Fig 2: Perspective view of the model domain used in the channeled sensitivity runs. It is a two-dimensional trough with sloped side walls. Shadings indicate flow height (top) and speed (bottom).

deformed layer. The critical depth is determined from the force balance containing the slopes of both the upper and lower boundaries of the flow. The bottom drag stress is calculated from the Bingham viscosity and the local vertical velocity gradient. The velocity gradient is determined by fitting a parabolic velocity profile in the deforming layer. This is constrained by a no-flow condition at the bed and an integral equation imposing the depth-averaged speed.

An Eulerian-based numerical solution method is used. Inputs to the model are the bathymetric profile, the location and geometry of the initial failure block, the viscosity and critical yield stress.

Numerical experiments

Initial numerical experiments were conducted with a plane slope. An example of the model output is given in Figure 1. Although this provided significant results, it was not possible to clearly distinguish the relationship between run-out distance and some of the controlling parameters because the shape of the debris flow changed in both horizontal directions. In light of this, the rest of the model runs were performed with a sloped seafloor indented with a channel aligned with the axis of the modeled flow (Figure 2).

Table 1 lists the model input parameters. All model runs were conducted for a fluid density of 1,400 kg/m³.

The run-out distances were taken as the length between the initial and final location of the face of the mud volume.

Yield Stress (kPa)	Kinematic Viscosity (m ² /s)	Initial Flow Height (m)	Bottom Slope
0.2	0.02	15	0.035
0.4	0.04	20	0.07
0.8	0.08	30	0.14
1.5	0.11	40	0.21
3.2	0.2		
8.0			

Results

The results (Figures 3 through 9) show the run-out lengths computed for the four input parameters given in Table 1. Figure 3 shows the relationship between run-out length and Bingham yield stress for five values of the kinematic viscosity. The control of run-out lengths by initial height and bottom slope are shown on Figures 4 and 5, respectively.

The run-out length to yield strength relationships shown in Figure 3 indicate that when the flow is constrained in a channel the yield stress controls the run-

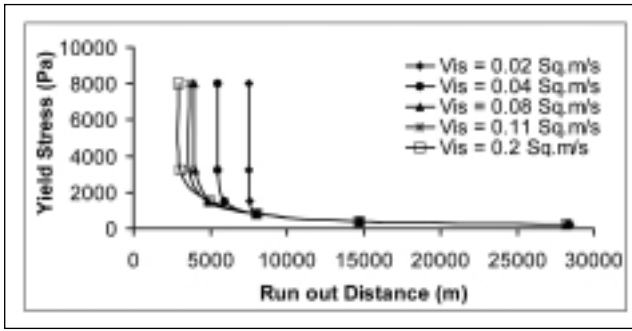


Fig 3: Run-out distance versus Bingham yield stress for a channel flow for constant slope (0.07) and initial height (30m).

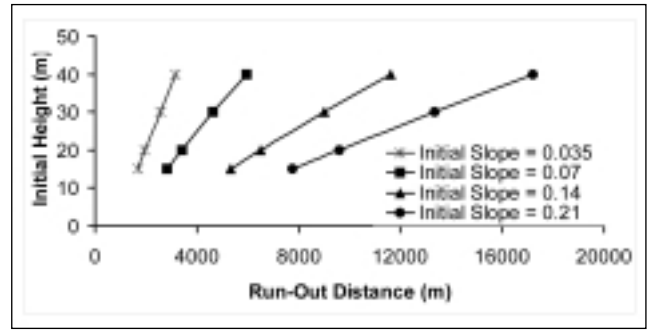


Fig 5: Run-out distance versus the height of the initial failure for constant yield stress (1500 Pa) and Bingham viscosity (0.11 m²/s)

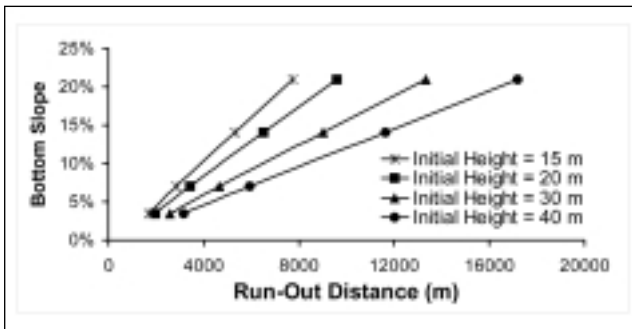


Fig 4: Run-out distance versus bottom slope for constant yield stress (1500 Pa) and Bingham viscosity (0.11 m²/s)

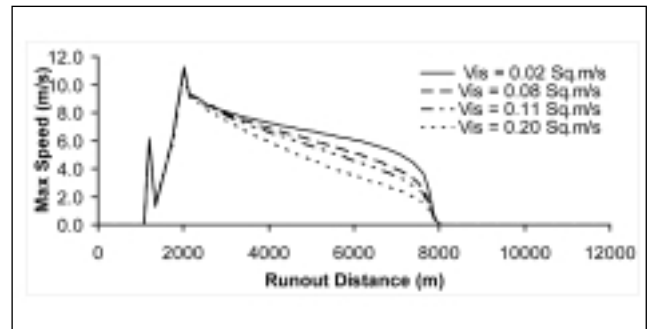


Fig 6: Debris flow speed profiles for five values of the kinematic viscosity where the yield stress (800 Pa), slope (1%) and initial failure height (30m) are held constant.

out length for constant values of the initial failure height and the slope. These curves represent five different values of the kinematic viscosity. These results emphasize how low values of the Bingham yield stress result in long run-out distances. The relative slope of the curve below a value of about 2 kPa clearly demonstrates the sensitivity of the run-out distance to variations in this parameter.

The plots shown on Figure 4 demonstrate a linear relationship between the bottom slope and the run-out length when the Bingham parameters of yield stress and dynamic viscosity remain the same. These results are explained by the decreasing thickness of the upper, non-deforming layer as the slope increases.

The effect of initial failure height on the run-out length of the debris flow is shown on Figure 5 for a range of bottom slopes. The relationships are linear, with sensitivity to the initial height increasing at the large slopes. Other investigators (Marr et al. 2002; Issler et al. 2003) have used the initial volume of the flow. The trough shown in Figure 2 has sloped sides, so the volume-to-height function is not quite linear. Therefore, these results do not directly compare with the power-law relationship between initial volume and run-out distance that was demonstrated by Issler et al. (2003). However, our results represent a very simple situation where the flow geometry of each case is essentially the

same. Issler et al. (2003) developed their relationship from field data. It is difficult to assess the role of differences in the shape of the bottom profiles on the run-out distances in their cases.

Although the kinematic viscosity of the Bingham fluid does not affect the run-out length of the debris flow, it is important in controlling the speed. Figure 6 shows a series of model results for the viscosity values shown in Table 1 using a yield stress of 800 Pa, a slope of 1%, and an initial failure height of 30m. The speed values shown on this figure are the maximum values that occurred at each point as the flow passed. Comparison with the examples shown on Figure 2 emphasizes this difference. Figure 2 shows that the speed is associated with the head and downstream portion of the debris flow that can be moving when the upstream end has already stopped. As expected, lower viscosities are associated with higher speeds.

Because, for engineering purposes, it is often useful to use a numerical model to estimate the speed that a debris flow can attain, we conducted an additional set of model runs using the plane slope geometry shown on Figure 1. In this way the relative shapes of debris flow could be modeled. Figure 7 shows these results of sensitivity runs where all values except the kinematic viscosity were kept the same. Here the final outline of each debris flow is shown, and it is seen that there is a

systematic change in the aspect ratio defined as the maximum length divided by the maximum width. The higher the viscosity is, the higher the value of this ratio.

Figure 8 shows the variation of the shape aspect ratio as a function of viscosity for different values of the yield stress. The greatest variations of the aspect ratio occur when the lower values of the yield stress are used in the

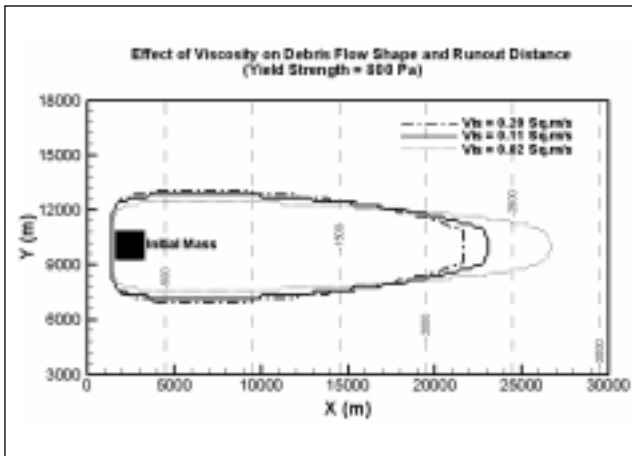


Fig 7: Outlines of the final shape of debris flows on a plane slope that are distinguished by viscosity. Here the yield stress = 800 Pa, slope = 1% and initial failure height = 30m. The highest viscosity produces the largest length to width aspect ratio.

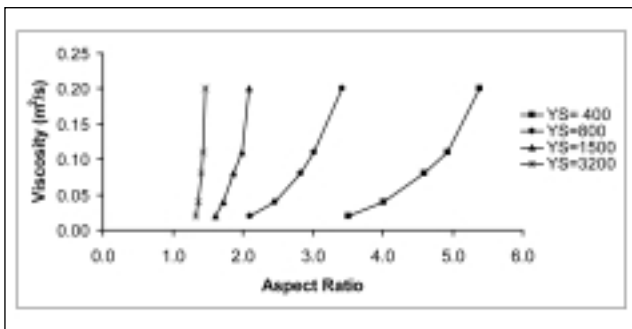


Fig 8: Debris flow aspect ratio for different kinematic viscosities where the slope (0.07) and initial height (30m) are the same in all model runs.

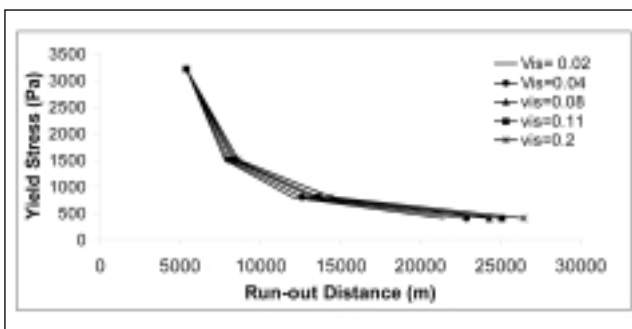


Fig 9: Run-out distance versus Bingham yield stress for a flow on a plane slope (0.07) where all model runs were all runs that used an initial height of 30m. Viscosity is in m²/s.

model run. This seems reasonable but the finding that the largest aspect ratios are associated with the highest viscosities may be counter intuitive. The speeds of the downslope and cross-slope flow components are controlled by the viscosity and the slopes of both the upper and lower flow surfaces. The difference between the slope components has a greater effect on the relative speeds of the downslope and cross-slope flows when the viscosities are greater.

Figure 9 is provided as a comparison to the results shown on Figure 3. The principal difference is that the former comes from modeled flows on a plane slope and the latter for channeled flow. Clearly, where the two-dimensional shape is allowed to change, the viscosity affects both the aspect ratio and the run-out length.

Discussion

The results of the systematic sensitivity tests are intended to be useful for estimating the non-Newtonian fluid parameters from debris flow deposits. Engineering applications often require a reverse-analysis approach. Modern deep-sea surveying methods can accurately map the extent and thickness of debris flow deposits. However, it is not surprising that attempts to make direct measurements of the Bingham fluid properties from samples of these deposits have not resulted in meaningful values. These deposits have undergone considerable material-property changes as they have aged. Consequently, the practice is to use numerical models to estimate the Bingham yield stress and viscosity properties with a trial-and-error process. Once a model based on these parameter values has been shown to adequately reproduce several measured deposits originating from similar source material, it is possible to use the model to predict future debris flow run-out behaviors.

Many investigators have noted that the final deposit thickness is controlled by the yield strength (Marr et al. 2002; Locat & Lee 2002, and others). If the debris flow behaves as a true Bingham fluid in contact with a solid and undeforming substrate then

$$\tau_y = h_z (\rho_d - \rho_a) g \sin \theta \tag{1}$$

can be used to directly evaluate the Bingham yield stress (τ_y). Here ρ_d is the mud density, ρ_a is the ambient water density, θ is the gravitational acceleration constant, and q is the slope of both the seafloor and the top of the debris flow as these are often very nearly the same debris flow deposit.

However, in many cases the debris flow was influenced by one of several types of lubricating layers. In these

cases the final run-out distance would be expected to be large and the yield stress conditions more complex than given by Equation 1.

Other methods are available. For example Locat & Lee (2002) provide a relationship between the liquidity index, flow thickness and the yield stress that can be applied to core samples from debris flow deposits to assess the fluid parameter at different points in a flow. Schwab et al. (1996) demonstrated that, so long as the water content of clasts is greater than the matrix in a debris flow deposit, the clast size can be used to evaluate the yield stress of the flow as it was occurring.

It appears that the interaction of the debris flow with the antecedent sediments has not been given adequate attention in many recent case studies. Prior et al. (1984) note this behavior in their description of the Kitimat Fjord debris flow. It is clearly an important consideration. Commonly, where marine debris flow deposits are found, there is a relatively steep slope above relatively flat seafloor underlain by a combination of layered sediments and previous debris flow deposits. The steep slope is there because the underlying material has the strength to support it. However, it can be made locally unstable by any of a variety of triggering processes.

During an event, the debris flow travels down the steep slope, usually gaining speed. Whether or not it attains the threshold speed needed to initiate hydroplaning of the nose, the flow can run beyond the bottom of the steep slope and out on to the nearly flat-lying antecedent sediments. Typically the upper tens of centimeters of these sediments have very high water content, and thus they provide a lubricating layer upon which the debris flow can glide. This is not to neglect the role of water trapped beneath a hydroplaning muddy debris flow as proposed by Mohrig et al. (1999). We simply point out that trapping of such a high water content layer is not necessarily dependent on the hydroplaning condition. However this layer originated, it will have a profound effect on the behavior of the debris flow, provided it is sufficiently coherent so that this water cannot dissipate within the flow itself.

Relatively high water content of the seafloor sediment can also account for the observation that remobilization of antecedent deposits is less commonly observed in submarine flows compared to their terrestrial equivalents. That is, the high water content of the seafloor sediments provides a lubricating layer that isolates the shear stress due to the debris flow from the antecedent sediments, allowing it to override them. Hydroplaning of coherent debris flows, or internal circulation within the head of a semi-consolidated debris flow, would help the head to pass on top of the antecedent deposits with minimal disturbance of the weak, high-water-content

upper sediments. In this circumstance, much or all of the shear deformation can be transferred to the lubricating layer. Here it is possible for the bulk of the debris flow to become a passenger layer. This probably explains the commonly observed texture of marine debris flows in cores. These layers can be readily distinguished by a pattern of mud clasts in a mud matrix. Such deposits are found many tens of kilometers from their sources, and it is difficult to understand why this delicate texture can be maintained if the deformation were within, rather than beneath, the flow.

However, when such remobilization does occur it can seriously affect a modeling analysis of existing deposits. Figure 10 shows a clear example of such an event. This figure, generously provided by Michael Schnellmann, shows a 3.5-kHz high-resolution seismic cross section of the Weggis slide, debris flow, and turbidity deposits that developed in Lake Lucerne (Switzerland) as a result of a magnitude ~6.2 earthquake in the year 1,601 AD (Schnellmann et al. 2005). This complex is about 2 1/2 km long and 3 km wide. The section shown in Figure 10 is representative of the central third of the deposits. On either side, the debris flow passed over the antecedent layer sediments without significantly deforming them. In this central portion of the depositional complex, the data show that the debris flow, clearly indicated by the chaotic acoustic reflections, mobilized the antecedent sediments. Both the flow and the underlying sediments are Holocene muds with similar compositions and densities. The disruption of the antecedent sediments appears to have been accomplished by the rapid loading that developed both shear and normal forces. These previous deposits were displaced along a basal surface, with some being incorporated into the flow, while the rest were deformed in folds and thrusts. The debris flow passed beyond these thrust lobes with no further disruption of the underlying layered sediments. Schnellmann et al. (2005) attribute the deformation of the antecedent sediment to the weight and impact of the soil mass that descended from the slide that triggered the flow.

The pattern of deformation shown in Figure 10 indicates that a portion of the flow was sufficiently thick to momentarily mobilize the underlying layered sediments. These, in turn, were thrust along by the fluidized mass behind them. To the sides of this central area the loading was not sufficient to mobilize the antecedent sediments. There, and beyond the thrust area, the debris flow must have been isolated from the underlying sediments by a lubricating layer related to some combination of high-water-content surficial sediments and debris flow hydroplaning. The data clearly show that both a gravitational body force and a transmitted shear stress can be important in mobilizing antecedent deposits. In cases where this mobilization of the underlying sediments occurs, the total volume of

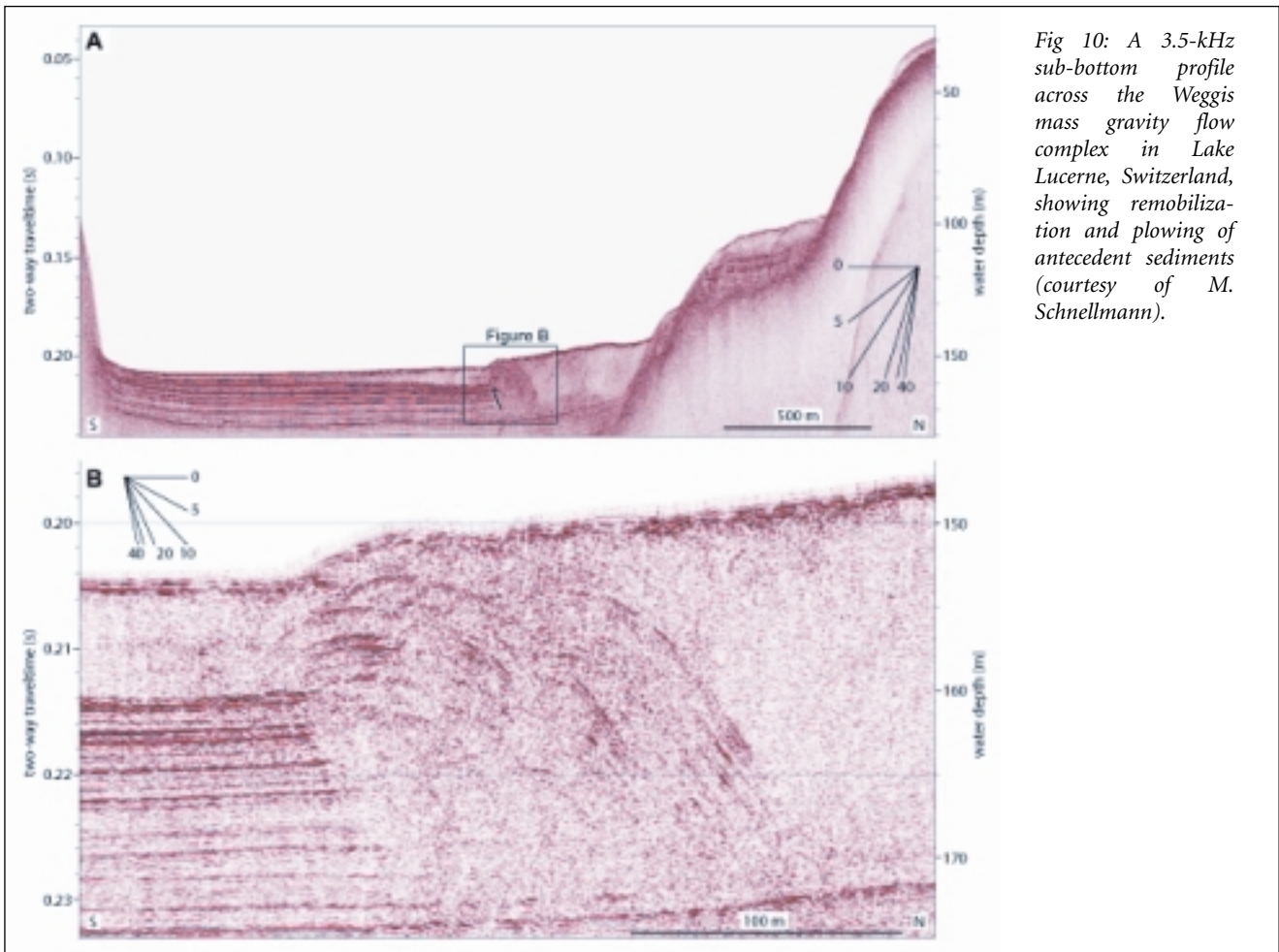


Fig 10: A 3.5-kHz sub-bottom profile across the Weggis mass gravity flow complex in Lake Lucerne, Switzerland, showing remobilization and plowing of antecedent sediments (courtesy of M. Schnellmann).

the debris flow can greatly exceed the volume of the original slide that triggered it. This added volume, along with the variable thickness of the debris flow, introduces significant complications for the selection of Bingham fluid parameters to be used in simple models that do not resolve these aspects of debris flow behavior.

From these considerations it appears that a lubricating layer not only affects the run-out length, it also alters the ability of a submarine debris flow to mobilize antecedent sediments. This layer can virtually eliminate the shear coupling between a coherent flow and the underlying sediment. This explains the observation made by Mohrig et al. (1999) that terrestrial debris flows commonly remobilize antecedent sediments while it is rare in the marine environment. We pointed out earlier that a common source of marine debris flow is the lower portion of a continental slope, just above the adjoining deep seafloor where the bottom slope is significantly less than the slope above. In these conditions the debris flow starts by passing over a firm slope and then flows out over the nearly flat-lying sediments with high near-bed water content. However, if the flow is long, the lubricating layer that initially supports the debris flow

can become depleted near where the flow leaves the steep slope. Depending on the nature and thickness of the lubricating layer, a certain length of the flow will pass until the depletion of the lubricating layer is complete. On the other hand, the model results presented on Figures 2 and 3 show that the inner portion of the debris flow can be at rest as a deposit while the outer portion (nearer the head) is still flowing. On the plane slope used in these scenarios there is a length scale associated with the moving portion of the flow. Whether the lubrication will be fully depleted depends on the relationship between the length of flow that must pass to deplete the lubricating layer and the length scale of the flowing portion of the debris flow.

In the light of these observations it is clear that the quantitative analysis of debris flow deposits should involve considerations of the fluid properties of a sediment mass as it was flowing and the conditions of the underlying and surrounding sediments. The fluid properties are likely to change along the length of the flow. Gravitational loading and shear coupling with the underlying soils may be sufficient to mobilize these and thus add to the flow volume. Even after the flow speed falls below the threshold for hydroplaning, the flow

may continue to exhibit very mobile behavior because of the high water content of the surface sediments that are being overridden. To proceed with an analysis there needs to be good consideration as to whether these effects are appropriately accounted for in the modeling. In some cases it may be sufficient to select equivalent Bingham fluid parameters that cause the numerical model to reproduce the gross geometry of the observed deposits. However, this can lead to problems in matching the volumes if remobilization of the underlying sediments has occurred.

Overall there needs to be a reconciliation between the requirements of engineering applications for meaningful and useful analyses of past and possible future flow behaviors and the complexities of the natural world. Actual applications vary from situations that are simple and can only be well represented with rather straightforward modeling, to those which are complicated by effects that can only be represented in the more sophisticated numerical models, and finally to those situations that are too complex to be quantitatively modeled. In simple cases the results herein presented can be applied directly. In some of the more complicated cases, appropriate use of "process-equivalent" parameter values can be used as long as the actual behavior is known and appreciated.

The results of this study show that the yield stress at the time the debris flow occurred can be estimated from the measured thickness of the resulting deposit, the slopes of the underlying seafloor and the surface of the debris flow deposit. Where the measured debris flow deposits have relatively simple geometries, the width-to-length aspect ratio can be used to estimate the viscosity of the flow. This can be accomplished through an appropriate simulation with a numerical model. The antecedent bottom geometry, failure height and volumes can be measured with modern marine surveying instruments. Thus, with adequate attention to potential limitations, the analyses can be reasonably well closed in many practical circumstances.

Conclusions

A two-dimensional layer-averaged numerical model was used to explore the dependence of debris flow run-out on input parameters, using simple and consistent bottom geometry. The effects of gliding on a lubricating layer and hydroplaning are not represented in the numerical model. The results show that the dominant control for the run-out length is the Bingham yield stress. In most situations this control is so dominant that the effect of the viscosity can be disregarded and the value of the yield stress at the time of the flow can be estimated from the deposit thickness, along with

measurements of the slopes of the antecedent seabed and the deposit surface. Although the kinematic viscosity is of little importance in controlling the run-out length, it is effective in controlling the speed and the minimum slope of the flow. Under proper conditions the choice of values for this viscosity can be narrowed based on the width-to-length aspect ratio of unconfined or weakly confined flows. The run-out length varies in a linear fashion with both initial failure height and the bottom slope. The effect of the initial failure height is most pronounced on the higher slopes. This is similar to the effect of the bottom slope, which increases the run-out length the most when initial height is largest.

The results are intended to provide guidance in the selection of Bingham fluid parameters in those studies where numerical models are used to simulate, and even predict, the behavior of debris flows and mudflows at prototype scale. Here it is not possible to make meaningful direct measurements of these parameters, because the conditions of the deposits have changed from those that existed during the flow phase. The choice of the fluid parameters also involves understanding other factors that control the flow and run-out of debris flows.

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