THE GENERAL BEHAVIOR OF MASS GRAVITY FLOWS IN THE MARINE ENVIRONMENT

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Abstract

Deep sea turbidity currents, mud flows, and debris flows have been the subject of a number of industry and government studies over the past two decades. While evidence of these flow events are common in a wide variety of continental slope and rise locations, the mode, scale, and frequency of these events have been shown to vary widely from place to place. Based on over more than a dozen field and modeling projects, we present an overview of the controls, scale, flow type, and flow behavior. The most general controlling factors are the type and scale of the triggering event, the slope and morphology of the seafloor, and the material properties of the flow. In this overview we focus on details of the evolving flows that need to be included in quantitative analyses with numerical models.

1. Introduction

Mass gravity flows include a variety of natural phenomena that are characterized by the near-bottom downslope flow of sediment and water. In the marine environment these take on a number of specific characterizations ranging from thin suspensions of sediment to flows of fluid mud, some with relatively high values of density.

In this paper we consider the interplay between the form of the mass gravity flows and the seafloor conditions where they occur. This includes the type and scale of the triggering event, the relevant seafloor morphology, and the physical properties of the materials associated with the flows. Many of the flow types demonstrate a remarkable degree of scale independence. The appearance and gross behavior of the flows are similar over about five orders of magnitude ($\sim 10^{-2}$ to $\sim 10^{3}$ km). However, the specific behaviors, including flow type, flow speed, erosiveness, run-out distance, and deposit thickness and width, as well as the ability to disrupt antecedent sediment, vary greatly.

This is a synthesis of information learned from a large number of studies of marine mass gravity flows in a wide range of deep sea environments. It is incorporates published research findings. We intend to provide an overview of the subject as a framework for guiding evaluations of these geohazards and for future studies.

2. Flow Types in the Marine Environment

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. Middleton and Hampton (1973) discuss the whole range of mass gravity flows, including uncommon examples such as topples and grain flows. The most common forms encountered by the offshore industry are turbidity currents, debris flows, and mud flows. Gani (2004) showed that these flows are distinguished by four characteristics: sediment concentration,

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sediment-support mechanism, flow rate, and rheology. Of these, rheology is the most diagnostic.

3. Event Triggers

In almost all cases, marine mass gravity flows are started abruptly by a triggering event. These control the flow type. The most common trigger is some form of gravitational soil mass failure. These can originate in several different ways. Although steep parts of the continental slope often exhibit signs of mass gravity flows, steep slopes are not necessary. Mass gravity flows have been triggered on slopes as little as 1 or 2 degrees and continue to flow on slopes well less than 1 degree. Deposits can even indicate upslope flow, because the slope of the top surface is controlling.

Turbidity currents are often triggered by gravitational soil mass failures, but there are a number of other mechanisms that can start these flows. These flows tend to persist for much greater distances than other forms of marine mass gravity flows.

3.1 GRAVITATIONAL SLOPE FAILURES

Rotational and slab displacements are the two most common forms of gravitational soil mass failures. These events result from: 1) an increase in the force above a stability limit, 2) a decrease in soil material strength, or 3) a change in the slope geometry due to outside events. The failure envelope in a rotational collapse is a concave-upward curved surface. After a failure occurs, a distinctive scar is left. With proper measurements this can be used to estimate the volume of material that moved. Slab failures commonly occur when a layer of sediment resides on a stronger underlying soil and there is a distinct plane boundary between them. The plane boundary provides a sloped surface where stress concentrations develop. After a failure, mapping of this boundary permits an estimate of the sediment volume that moved during the event.

3.2 CAUSES OF SLOPE FAILURES

Whether submarine slopes are steep or gentle, they can remain stable for very long periods of time unless disturbed. Earthquake accelerations and sediment accumulations are examples of rapid and slow disturbances. During earthquakes the ground accelerations add to the destabilizing forces and, when combined with the existing internal stress field, can cause the slope stability criteria to be exceeded.

Ongoing sedimentation can slowly add to the total thickness of a weak sediment layer. As the thickness increases, the magnitude of the shear force across the plane boundary at its bottom can increase to above the point of stability.

Either slab or rotational failures can be caused by increased pore water pressure. This comes about in a number of ways. Collapse of grain-to-grain support is an example. Agitation by earthquake motions or fluctuating pore pressure due to steep storm waves causes loosely packed sediment grains to jostle and move into a tighter packing. During this process the overburden load is transferred from the grain framework to the pore water. The sediment mass suddenly loses its resistance to shear. The overburden is supported by the excess pore pressure. In these circumstances gravitational collapse can occur under small loads and low slopes. Venting of gas or pore water from underlying sediments can also create excess pore pressure.

Changes in the geometry of submarine slopes are the third general cause of gravitational soil mass failures. This can occur in several ways. The down-cutting of a submarine canyon or erosion in an adjacent tributary canyon can undercut a slope and cause it to become unstable. Some submarine slopes are actively growing. For example, the lower portion of the continental slope off Texas and Louisiana is characterized by the steep 900-m high Sigsbee Escarpment. This slope is deforming as a result of underlying creep in salt deposits. In the Caspian Sea, deep-seated compression due to converging continental plate movements expel liquid mud, forcing it upward where it can inflate isolated strata or erupt at the seafloor.

3.3 ORIGINS OF MUD FLOW EVENTS

Mud flows represent the same flow behavior as debris flows but tend to be more fluid. Outstanding examples occur in the relatively shallow water depths of marine deltas. Prior and Coleman (1977), and others, have shown the association of these features with wave-induced gravitational soil mass failures.

Mud volcanoes are remarkably similar in appearance to their igneous equivalents. These form both above and below the sea. They are common along the eastern margins of the Caspian Sea and are known in many ocean locations. Deep-seated tectonic processes squeeze fluid mud upward along passages that vent at the seafloor. The resulting discharges are mud flows that can last for hours or days.

3.4 ORIGINS OF TURBIDITY CURRENT EVENTS

There are several important triggers for turbidity currents. Turbidity currents triggered by sudden events such as gravitational soil mass failures, their resulting debris flows, or mud flows are considered short events. The duration of the turbidity current can be far longer than its triggering event because the current becomes elongated as it travels.

Very persistent turbidity currents also develop. Imran and Syvitski (2000) have described conditions at river mouths where the suspended sediment load is so high that the discharge plume sinks to the bottom as it enters the ocean (hyperpycnal flow). Only a few of the rivers of the world carry such high sediment loads, and then only for a few hours or days. When these flows reach the shelf edge they tend to continue as turbidity currents, often contained within a submarine canyon.

P. Traykovski et al. (2001) have found that low frequency storm waves resuspend muddy river plume deposits on the inner Eel River shelf off Northern California. In storms the wave orbital boundary layer becomes saturated with suspended sediment. A strong density contrast develops at the top of the wave boundary layer, which inhibits further upward dispersion of the suspended sediment. The thick sediment load, suspended by the strong fluid shear in the wave boundary layer, is drawn downslope by gravity. The result is an offshore transport of sediment which either reaches the shelf edge or dissipates on the outer shelf where the wave orbital activity diminishes.

4. General Flow Behavior

Debris and mud flows can be rapid (10s m/sec) or slow (1/10th m/sec). The whole mass of sediment and entrained water acts as a single fluid much like ketchup. The densities of these fluids vary from a little more than the surrounding water to values approaching those of the parent materials from which they derive. Elverhoi et al. (2000) and Harbitz et al. (2003) have identified four stages of debris flow events. These are: 1) initial failure (trigger event), 2) transition, 3) flow, and 4) deposition. The transitional stage follows the trigger event. The internal particle-to-particle structure is deranged and the material strength drops due to remolding as the soil mass begins to accelerate downslope. Submarine events also have an opportunity to uptake water. The details of these processes are poorly known (Harbitz et al. 2003).

Turbidity currents are different. These are suspensions of sediment grains in a turbulent flow. The suspension is most dense near the seabed and decreases to the value of the surrounding water at the top of the flow. Averaged over the whole height of the flow, these suspensions are on the order of 3 to 5 % by volume. A downslope flow of turbid water is said to "ignite" when it erodes as much, or more, sediment than is settling out. Under these conditions the mass of the turbid water increases and further acceleration occurs. The dynamics of stable turbidity currents necessitate that sediment particles are eroded at nearly the same rate as they settle to the bed. However, where the flow is accelerating, erosion tends to dominate and deposition occurs where the flow is slowing.

4.1 COMPOUND EVENTS

Although turbidity currents can form without associated debris or mud flows, the converse is rare. The triggering event and subsequent rapid downslope flow of the mud-rich debris flows cause high fluid shear at the upper boundary where the flow passes beneath the ambient water. The sediment in the debris flow is often weak and easily eroded. The resulting "cloud" of turbid water is accelerated by the boundary shear. This can reach the turbidity current ignition condition. Ilstad et al. (2004) have shown that a mud-poor debris flow can evolve directly into a turbidity current as excess ambient water penetrates the head. In other cases, the cloud of turbid water does not accelerate enough to reach the ignition condition, so that it slowly deposits its load and dissipates.

4.2 COMPOUND SCALES

Many of the subsea environments where mass gravity flows are of concern have complex histories. There are typically several cycles of sedimentation and erosion portrayed in the sculpted morphologies of the seafloor. Often some of these cycles are related to variations in the sea level and the supply of sediment brought about by the waxing and waning of the huge Pleistocene glaciers. A common result is that deposits of significantly different strength and water content alternate on the seafloor. Steep slopes on strong material often have systems of valleys. These can be active sedimentation sites collecting weak sediments. As the recent sediment deposits become thicker they can reach a point of instability. It is important to recognize this compound arrangement of potential trigger events because we have often found that strong and rare events are needed to cause the underlying slopes to fail. However, the weaker surficial deposits can be a much greater hazard because they can reach failure conditions more frequently.

5. Material Properties

Mass gravity flows are controlled, in large part, by the material of which they are comprised. However, this holds true in different ways for debris flows and turbidity currents.

Like their terrestrial counterparts, marine debris flows have a wide range of compositions; silt and mud are common constituents. The composition of a debris flow 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. 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 and Garcia 1998). However, in our experience the most common marine debris flows are not coarse-grained, have considerable clay content (> 25 %), and deform plastically. Most studies have found that a Bingham Fluid representation is adequate to represent all but coarse granular debris flows.

Sensitivity is the ratio of the undisturbed and remolded shear strengths. This comes about because a soil loses its strength when internal shearing disrupts the grain-to-grain soil structure. Strength decreases by factors of two to three are common (Locat and Lee 2002) and in extreme cases may be an order of magnitude or more (Locat and Demers 1988). Carbonate sediment tend to have high values because grains shatter and collapse.

The relevant material properties of debris flows are notoriously difficult to measure. These properties are transient, changing from the initial values as the soil mass fails, to the reduced strength during the flow, and then converting to yet other values as the resulting deposits dewater and age. For this reason, most attempts to study debris flows with numerical models are forced to treat the Bingham shear strength and viscosity as parameters to be fitted during model calibration.

The sediment properties associated with turbidity currents are generally those related to most sediment transport analyses. These define the erosion and deposition properties. Here again, the role of mud is important because as little as 8 to 10 % generally causes cohesive behavior in the seabed. Additionally, similar amounts of fine clay particles in the suspension settle extremely slowly, so that they serve to help perpetuate the current once started.

The erodibility of the seafloor sediment can be determined from a Shields Curve (Middleton and Hampton 1973) provided that it is entirely granular. Although there have been various attempts to develop equations to express cohesive sediment erosion parameters in terms of traditional geotechnical measurements, these are not widely accepted. Instead, the fluid stress threshold for erosion and the rate of erosion are determined is special apparatus (Briaud et al. 2001)

Once a turbidity current has accelerated to the ignition condition its stability is determined by a balance between the rate that new sediment is entrained in the flow and the rate that sediment is deposited. The deposition is controlled, in turn, by a balance between turbulent diffusion, which acts to diffuse the grains upward, and grain settling due to gravity. Thus, a quantitative analysis of a turbidity current depends on an accurate knowledge of the particle settling speed. This can be accomplished in any of a variety of grain size analysis methods. The caution is that the sediment grains in the bed are not a true representation of what the current is carrying, because fine and very fine grains travel much further than silt and fine sand. Therefore, samples need to be taken along a considerable length of the flow path before the average grain size distribution of the suspended sediment can be estimated.

6. Role of Antecedent Conditions

As mentioned earlier, it has been commonly observed that marine debris flows run out further than their terrestrial counterparts. One mechanism to explain this is hydroplaning at the nose. However, the flowing portions of debris flows can be 10s of kilometers long. An alternate explanation of this far-traveling behavior can be found in the low strength and high water content in the upper 10s of centimeters of marine sediments. Figure 1 illustrates this process. The stronger, more competent soil makes up the steep slope. When a gravitational soil mass failure occurs, a debris flow forms, and it accelerates downslope to emerge onto the more flat-lying marine sediments. The high water content in the upper sediments (~0.1 to 1.0 m thick) provides lubrication. The shear shifts from within the debris flow to the lubricating layer.

Evidence for this process is found in the common observation that soft mud clasts suspended in a mud matrix (i.e. a soft sediment breccia) often characterize debris flow layers in marine cores, even 10s of kilometers from their source. These clasts have been fractured and sheared in the initial downslope run of the debris flow. However, once the flow passes onto the nearly flat-lying sediments, the shearing ceases. In this way these delicate textured layers can be transported 10s of kilometers from their sources.

7. Erosion and Deposition

Both turbidity currents and debris flows are known to erode. This behavior in turbidity currents is much like that in rivers, where erosion is associated with accelerating conditions and deposition occurs as the flows slow down.

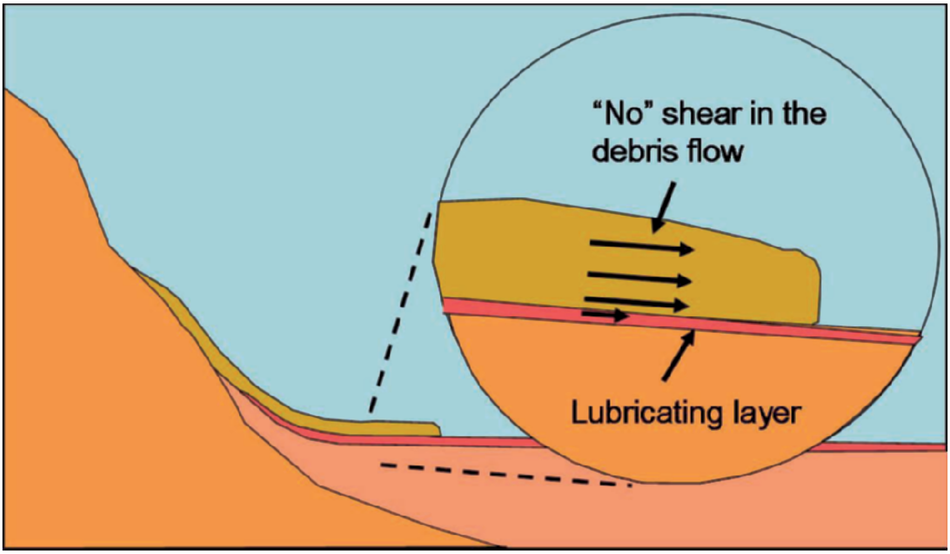

Figure 1. Schematic of a debris flow lubricated by the high-water-content sediment zone.

Not all debris flows erode. Usually, they simply pass over the seafloor sediment. When the surface of the antecedent sediments is weak, with a density close to that of the debris flow, it is possible for the basal shear to propagate downward into the underlying sediments. A thought experiment to illustrate this consists of envisioning pouring a small volume of ketchup onto a sloped board. This will run down and become thinner until it stops. Then, if another small volume is poured on top of the initial "deposit," both layers will move downslope together until they again reach a limiting thickness. Behavior of this type has been observed in natural debris flows (Schellmann et al. 2005).

8. Discussion and Conclusions

A geohazards investigation where ongoing mass gravity flow activity is suspected has four parts. Background data are used in an initial site evaluation and for the design of a survey. The survey leads to the creation of a geological model. Finally, numerical models are applied to both replicate past activity and to forecast future events.

Numerical models of turbidity currents and debris/mud flows play an important role in these investigations. Here it is assumed that the seafloor features and deposits are a record of past events. When good models demonstrate the capability of reproducing the physical features and deposits of the existing seafloor, they are thought to be trustworthy as indicators of the speeds, dimensions, and run-out lengths of potential future flows.

Models today are powerful but still incomplete. None follow the full sequence from the trigger event to the final run-out. Instead, sequences of models are typically applied, and these require various compromises to account for many of the behaviors discussed in this paper. Some behaviors, like the erosion of a cohesive debris flow to spawn a turbidity current, can be approximated. Others, like erosion due to a debris flow, have not yet been successfully developed.

From the above it can be concluded that there is a developing need in industry to increase our understanding of marine mass gravity flows. A number of projects such as Ormen Lange, Blue Stream, and Atlantis have accelerated our physical insights, as well as the development of both measurement methods and numerical models. However, there are many processes that are only now becoming recognized, and considerable work lies ahead.

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