Submarine landslides: advances and challenges[1]

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Abstract: Due to the recent development of well-integrated surveying techniques of the sea floor, significant improvements were achieved in mapping and describing the morphology and architecture of submarine mass movements. Except for the occurrence of turbidity currents, the aquatic environment (marine and fresh water) experiences the same type of mass failure as that found on land. Submarine mass movements, however, can have run-out distances in excess of 100 km, so their impact on any offshore activity needs to be integrated over a wide area. This great mobility of submarine mass movements is still not very well understood, particularly for cases like the far-reaching debris flows mapped on the Mississippi Fan and the large submarine rock avalanches found around many volcanic islands. A major challenge ahead is the integration of mass movement mechanics in an appropriate evaluation of the hazard so that proper risk assessment methodologies can be developed and implemented for various human activities offshore, including the development of natural resources and the establishment of reliable communication corridors.

Key words: submarine slides, hazards, risk assessment, morphology, mobility, tsunami.

Résumé : Le développement récent de techniques de levés hydrograhiques pour les fonds marins nous a permis d'atteindre une qualité inégalée dans la cartographie et la description des glissements sous marins. À l'exception des courants de turbidité, on retrouve dans le domaine aquatique les mêmes types de mouvements de terrain que sur terre. Par contre, les glissements sous-marins peuvent atteindre des distances excédant 100 km de telle sorte que leur impact sur les activités offshore doit être pris en compte sur de grandes étendues. La grande mobilité des glissements sous-marins n'est pas encore bien comprise, comme pour le cas des coulées de débris cartographiées sur le cône du Mississippi ainsi que pour les grandes avalanches rocheuses sous-marines retrouvées au pourtour des îles volcaniques. Un défi majeur auquel nous faisons face est celui de déterminer les aléas associés aux divers types de mouvements sous-marins ainsi que les risques associés à l'activité humaine, telle que l'exploitation des ressources naturelles et l'établissement de routes de communications fiables.

Mots clés : glissements sous-marins, morphologie, aléa, risque, mobilité, tsunami.

Introduction

The continuing development of natural resources, oil and gas in particular, either close to the continental slope or in deeper water, the growing need for sea-floor transport and communication routes, the pressure on coastal development (cities and harbours), the protection of the marine environment, and the impact of global changes are all responsible for the major advances in our understanding of the phenomena of submarine mass movements and their inherent consequences. In this context, we wish to review major advances made over the period 1984–2000 and identify the main challenges still ahead.

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The year 2000 coincided with the completion of the International Decade on Natural Disaster Reduction (IDNDR). Over the last 10 years, many opportunities (e.g., symposia, workshops, and conferences) were taken to underline the significance of landsliding not only as a morphological agent but also as a natural phenomenon with economical and societal significance acting both on land and underwater. During this period, two international symposia were held, Christchurch in 1992 and Trondheim in 1996. However, the last opportunity to review submarine mass movements, as a part of the International Symposium on Landslides in Toronto, was provided by Prior (1984). During this period, reviews related to submarine mass movement and related phenomena were provided by Lee (1989, 1991), Schwab et al. (1993), Hampton et al. (1996), and for some physical considerations by Leroueil et al. (1996) and Locat (2001).

Since the early 1980s, few major national and international projects have been directly related to the study of submarine mass movements. These projects have various acronyms, including ADFEX (Arctic Delta Failure Experiment, 1989–1992), GLORIA (a side-scan sonar survey of the U.S. Exclusive Economic Zone, 1984–1991), STEAM (Sediment Transport on European Atlantic Margins, 1993–1996), ENAM II (European North Atlantic Margin, 1996–1999), STRATAFORM (1995–2001) (Nittrouer 1999), Seabed Slope Process in Deep Water Continental Margin (northwest Gulf of Mexico, 1996–2004), and COSTA (Continental

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Slope Stability, 2000–2004). As illustrated later in the paper, these projects in various ways brought major advances in our understanding of submarine mass movements and their consequences.

After reviewing the typology of submarine mass movements, we address issues pertaining to the prefailure, failure, and the post-failure stages. We complete our coverage by discussing some elements of hazard and risk assessment related to submarine mass movements. At each step, we try to underline achievements and remaining challenges and illustrate some major technological developments.

Causes, classification, and characterization

The typology of submarine mass movements involves assembling complex phenomena into a framework that can be used to maximize our knowledge of their causes, their geomorphological and geotechnical characteristics, and the physics involved.

A compilation of the possible elements that can initiate a submarine landslide is presented in Fig. 1*a*. Some causes are unique to the marine environment, i.e., role of gas charging, diapirism, and wave action. Materials involved in submarine mass movements are as diverse as those on land, i.e., rock, soil, mud, and mixtures of all three. Because of the potential extent of submarine mass movements, we have to consider all the components of the phenomena, i.e., initiation, transition into debris flow (Norem et al. 1990), subsequent formation of a turbidity current (Normark and Piper 1991), and movement on the sea floor until final deposition. Here we must distinguish the cases where turbidity currents can be directly generated by hyperpicnal flows originating at the mouths of major rivers entering the ocean, as often seen in fjords (Syvitski et al. 1987; Mulder and Syvitski 1995), from those originating from mass movements or debris flows. To illustrate the continuity of the mass movement phenomena, we borrowed a diagram proposed by Meunier (1993) (Fig. 1*b*). This diagram has two axes, namely granular and cohesive, and takes into account the relative proportion of solids and water. Therefore, depending on the type of mixture (one or two phases), the behaviour of the mixture will be best analysed by soil–rock mechanics principles, fluid mechanics, or torrential hydraulics. This means, for example, that for mudflows, where the rate of movement is fast enough that there is no time for excess pore-water dissipation, the mechanics of the movement cannot be adequately explained by soil mechanics but rather by fluid mechanics principles. For a comprehensive review of debris-flow mechanics, the reader is referred to the work of Iverson (1997).

The various types of mass movements that can be involved are summarized in Fig. 2, which is an adjustment of the same classification proposed for subaerial mass movements by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee on Landslides (TC-11). Here, the only addition is that of turbidity currents. All the types indicated here are mutually exclusive, for instance, a slide cannot be a fall. Some types of mass movements, like slides, will be recognisable by the disrupted step-like morphology indicative of little displacement of the failed mass. In a slide, the displaced material moves on a relatively thin zone of intense strain. At the extreme case as for flows, the slide area will be emptied and the failed mass may be deposited many hundreds of kilometres away from its source (Schwab et al. 1996). In a fall, the displaced material descends mainly through water, falling, bouncing, and rolling. Of course, one type of mass movement can lead to another, e.g., a slide can transform into a flow. One could introduce subdivisions (e.g., Prior 1984; Mulder and Cochonat 1996; Norem et al. 1990), but the terms presented in Fig. 2 can cover most of the observed phenomena.

A first observation based on the above presentation is that if we wish to carry out a risk assessment related to submarine landslides, we must take into account the various components of the phenomenon, i.e., from failure initiation to the final deposition, which will require scientific consideration covering all the physics involved. As a contribution to this issue, Leroueil et al. (1996) proposed a general framework called geotechnical characterization of mass movements which incorporates three basic elements: (*i*) the materials, (*ii*) the slope movements, and (*iii*) the movement stages. These stages are as follows: (*i*) the prefailure stage, when the sediment or rock mass is essentially in a state of equilibrium and intact; (*ii*) the failure stage, in which the onset of failure is characterized by the formation of continuous shear bands or surface through the entire mass originating from various causes; (*iii*) the post-failure stage, which involves the behaviour of the sliding mass until it essentially stops; and (*iv*) the reactivation stage, which relates to movements on preexisting failure planes or failed masses.

The driving mechanisms of submarine mass movements will vary according to the causes but also according to the environment in which the mass movements will occur. For example, the Grand Banks slide was triggered by an earthquake, but the open ocean margin provided ideal conditions for the development of a large turbidity current. In the case of the debris flows on the Mississippi Fan, their large travel distances can only be explained by the presence of a well-developed channel system (Schwab et al. 1996; Locat et al. 1996). Therefore, considering the various stages of mass movement is an important step in bringing together the various driving mechanisms. In many cases, we have observed that at the failure stage, soil or rock mechanics principles are needed to explain or predict the stability. However, for the post-failure stage, very often the approach must rely on fluid mechanics principles.

Geomorphology and architecture

The initial knowledge of potential problems, in a given area, is often evidenced by geomorphological features which may suggest that the sea floor or slope has been disrupted in a catastrophic manner. The geomorphological setting of a landslide constitutes its final stage unless it is reactivated and, in itself, is a major revealing factor of the potential problem at a local and regional scale. With the development of multibeam techniques (Mitchell 1991; Li and Clark 1991; Prior and Doyle 1993; Hughes Clarke et al. 1996), differential global positioning systems (DGPS), and high-resolution seismics (HRS) (Davies and Austin 1997), we can now produce precise bathymetric maps of near air-photograph quality (Bellaiche 1993; Urgeles et al. 1997) and define the

Fig. 1. (*a*) Causes of submarine landslides. Elements in bold are commonly most significant. *F*, factor of safety. (*b*) Schematic view of mass movements made of mixtures of solid and water at various stages of mixing and as a function of solid characteristics (one- or two-phase flow) with indication of the physics involved in the phenomena (modified from Meunier 1993).

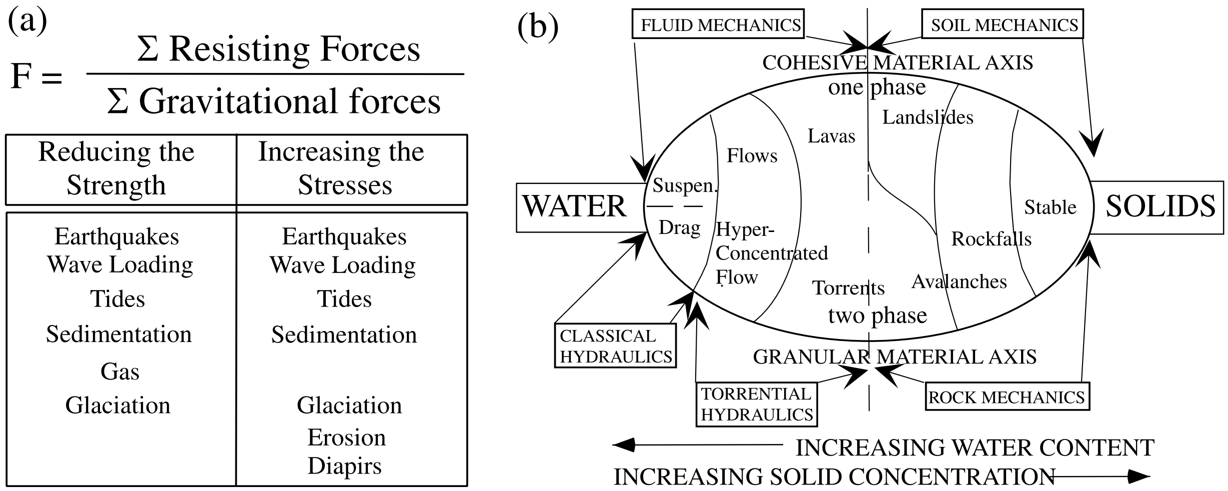
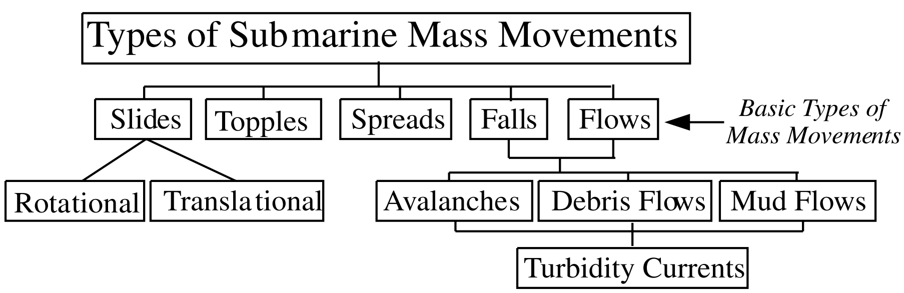


Fig. 2. Classification of submarine mass movements adapted from subaerial classification proposed by the ISSMGE Technical Committee on Landslides (TC-11).



precise stratigraphy of a landslide body. This is why one of the major achievements of the last decade has been the rapidly increasing use of multibeam surveys over the whole water world, i.e., both marine and fresh water (Prior and Doyle 1993; Locat et al. 1999; Locat and Sanfaçon 2000). The analysis of subaerial landslides has typically been done with an adequate knowledge of the morphology and stratigraphy, not withstanding the mechanical properties and pore-water conditions. For submarine landslides, it is therefore only recently that we can count on data of similar quality. Instead, most of the analyses had to rely on side-scan sonar and sparsely spaced, single-beam, echo-sounder lines, which had major limitations in terms of positioning and resolution. Physiographic features were identified only by interpolating between a series of survey tracks. The resulting mapped morphologies bore only a crude resemblance to the actual sea-floor features. This was particularly true for large landslides (Moore and Normark 1994; Schwab et al. 1991).

Because of the need to achieve a three-dimensional (3D) description of the geological and geotechnical environment, HRS has been developed significantly during the same period with the implementation of Huntec, SEISTEK, and CHIRP seismic systems often directly coupled with side-scan sonars. The use of 3D seismics has for a long time been an activity restricted to the oil and gas industry, but it has recently found application in marine Quaternary stratigraphy (Davies and Austin 1997). More recently, two-dimensional (2D) and 3D seismic data have been integrated in the study of sediment deposition (Driscoll and Kramer 1999). In parallel, the development of synthetic seismograms has provided a bridge between modellers and geophysicists. These techniques are now integrated in the study of submarine mass movements (e.g., project COSTA).

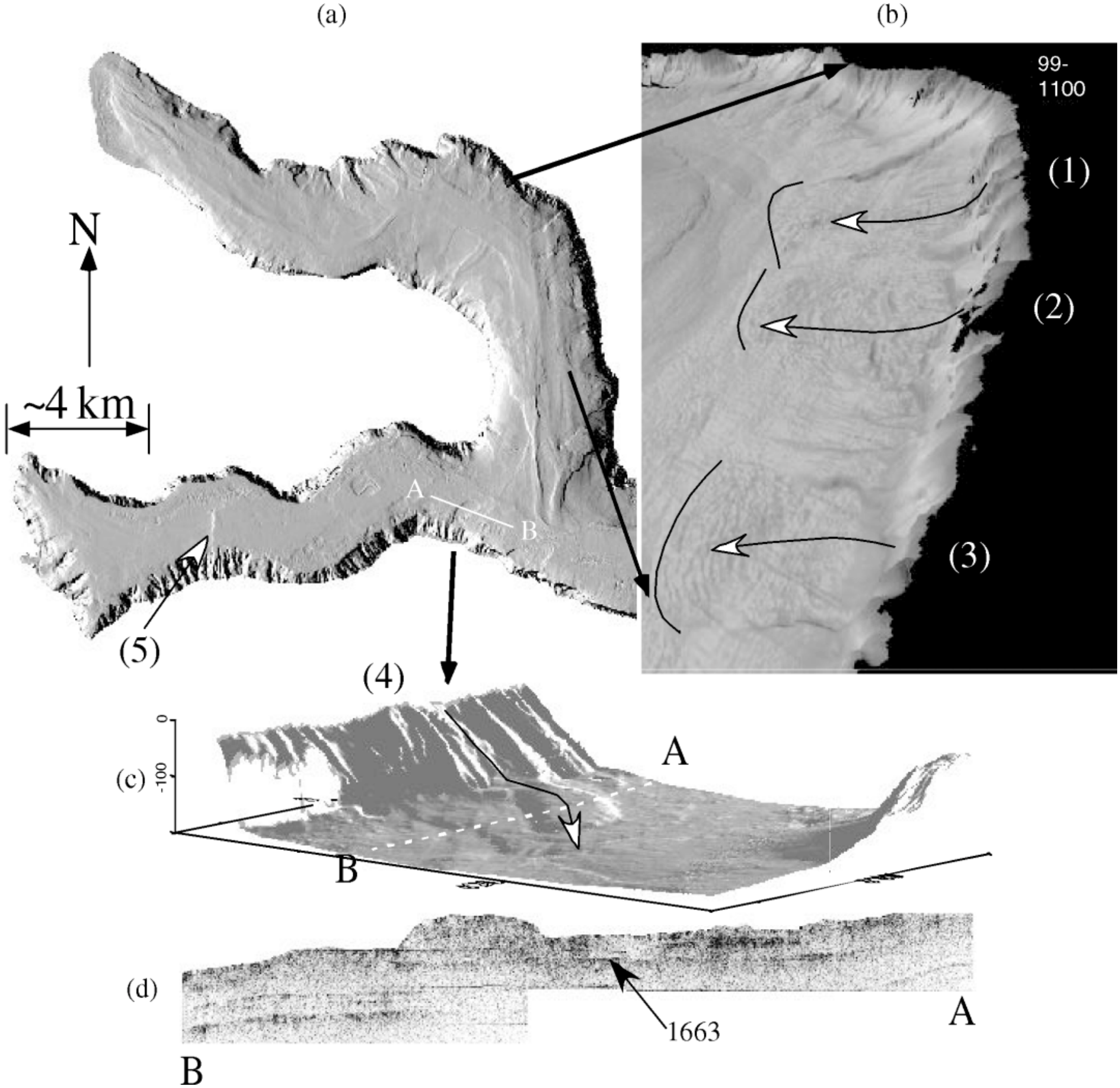
A few examples are briefly presented to illustrate the use of multibeam and HRS surveys in the study of submarine mass movements.

Saguenay Fjord, Quebec, Canada

Saguenay Fjord was, in 1993, among the first sites where a multibeam sonar survey was carried out to map submarine landslides (Couture et al. 1993; Prior and Doyle 1993; Hampton et al. 1996). The fjord is located 200 km northeast of Québec City, Canada. The Saguenay Fjord multibeam survey shown in Fig. 3*a* covers the upper part of the fjord where the water depth ranges from 0 to 225 m. As part of a major project looking at the same area, the site was revisited in 1997 after a major flood event (Kammerer et al. 1998) and again in 1999 (Figs. 3*a*–3*c*).

The Saguenay Fjord region has had frequent major earthquakes (e.g., magnitude 6.3 on the Richter scale in 1988), the largest historic one occurring in 1663 (Locat and Leroueil 1988; Locat and Bergeron 1988; Pelletier and Locat 1993; Syvitski and Schafer 1996) for which an equivalent magnitude of 7 on the Richter was given. It is believed that

Fig. 3. Morphology of the upper part of the Saguenay Fjord, Quebec, Canada, showing a 3D representation of multibeam bathymetry from the 1999 survey. (*a*) General view of the upper Saguenay Fjord area. (*b*) Enlargement showing fjord wall mass movements (mostly spreads) at 1, 2, and 3. (*c*) Flow failure at 4, with a seismic line across the slide area shown in (*d*), and the escarpment of a liquefaction failure at 5. Vertical scale in metres. (*d*) Seismic survey across the Pointe-du-Fort slide. 1663, estimated seafloor position in 1663. The water depth ranges from 0 to 225 m.



this earthquake triggered a series of major land and submarine slides, the largest subaerial one being the St. Jean Vianney slide, with a total volume of more than 200 million cubic metres. At the same time, major submarine landslides took place in the upper reaches of the fjord (Locat et al. 2000). Although the triggering mechanisms are the same, various types of mass movement took place, including spreads (1, 2, and 3 in Fig. 3*b*), and flows (4 in Fig. 3*c*, 5 in Fig. 3*a*, with the escarpment of the flow failure which went around the Pointe-du-Fort flow shown in Figs. 3*c* and 3*d*). This major earthquake of 1663 is believed to be responsible for triggering of all these landslides, which generated a 5–15 m thick turbidite in the deeper part of the fjord, a few kilometres to the east (Perret et al. 1995).

A seismic survey across the Pointe-du-Fort slide is shown in Fig. 3*d* and illustrates the signature of the slide which took place in a Laflamme Sea clay deposit flanking the south shore of the Baie des Ha! Ha!. The average thickness of the flow failure deposit is about 15 m and the total run-out distance is about 800 m. A transparent layer can be seen on both sides of the slide and represents the mudflow deposit generated by the large liquefaction failure which originated in the centre of the Baie des Ha! Ha!. The Pointe-du-Fort slide (4 in Fig. 3*c*) partly dammed this mudflow deposit, which is thicker on the upstream side of the slide.

Palos Verdes slide, California, U.S.A.

The Palos Verdes slide (Fig. 4) is located along the San Pedro escarpment just offshore of Los Angeles. The sea floor lying at the base of the escarpment is the San Pedro Basin, which had long been recognised based on seismic reflection logs (Gorsline et al. 1984). The slope itself is formed of sedimentary rocks dipping between 10 and 15°. The slope is eroded by a series of gullies 2–4 km apart. The base of the slope would more or less coincide with the trace of the San Pedro fault (Bohannon and Gardner 2001). The slide took place along a steep escarpment, mobilized into a debris avalanche, and travelled a distance of about 8 km out onto the adjacent basin floor (Fig. 4*b*). The head scarp is about 600 m high and the slope varies between 10 and 20°. The debris was dispersed over a wide area shown in Fig. 4*a*. From seismic records the thickness of the debris deposit varies from about 20 m in the lower part of the slope to less than 1 m about 8 km away from the base of the slope, with an average thickness of 5–10 m (Fig. 4*b*). The coupling of both the seismic survey and the multibeam survey does provide a comprehensive picture of the nature of this slide and its extent. An analysis of the run-out distance of the debris indicates that the initial sliding mass was large enough and had sufficient potential energy to trigger a tsunami and reach the observed run-out distance (Locat et al. 2001). A detailed observation of the escarpment and the shelf edge reveals that the erosion process is continuing and may be in a northwestward direction (see X in Fig. 4*a*).

Canary Islands rock avalanches, Spain

The Canary Islands rock avalanches have been initiated on the non-buttressed flanks of the island, which is bounded by the rift systems where most volcanic eruptions take place (Fig. 5). The avalanches retrogressed almost to the top of the island (1500 m elevation) in El Hierro (Fig. 5), 2400 m in La Palma, and 3700 m in Tenerife, which has the third highest oceanic volcano on Earth after Mauna Loa and Mona Kea in Hawaii (Moore et al. 1992, 1995). These avalanches travelled distances of between 50 and 100 km down to ocean depths of up to 4000 m and involved volumes of up to several hundred cubic kilometres (Urgeles et al. 1997, 1999; Watts and Masson 1995, 1998). The El Hierro submarine rock avalanche shown in Fig. 5 covers an area of 2600 km^2 for a volume of about 150 km^3 (Urgeles et al. 1997). This type of mass movement is very similar to those reported by Moore and Normark (1994) for the Hawaiian Islands. Major rock avalanches are now reported around many volcanic islands (e.g., Elsworth and Voight 1995; Voight and Elsworth 1997; F. Chiocci, personal communication, for Stromboli Island).

The aforementioned selection of submarine mass movements has illustrated how the new developments in both multibeam and seismic surveys have enabled us to achieve a fine description of these phenomena. For the future, the challenge lies in integrating this morphological and seismic information with geotechnical profiles to provide a 3D view of the rock or soil properties involved in mass movements or along a slope. Some direction and examples are provided by Hart (1999), who has coupled 3D seismics with rock properties to create a 3D distribution of rock properties.

Geotechnical investigations of submarine landslides

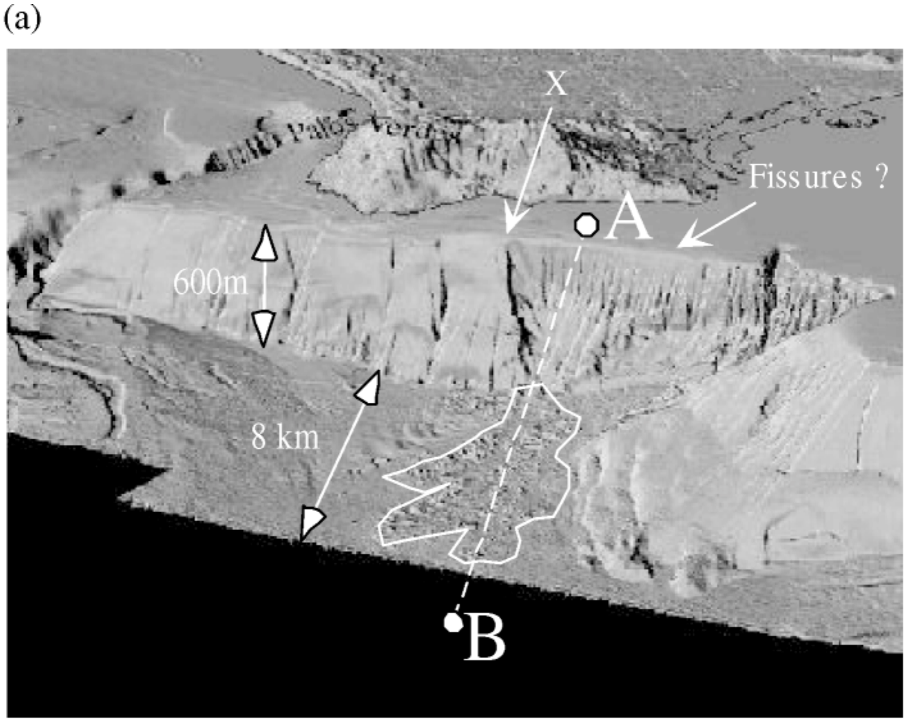
Coring and sampling

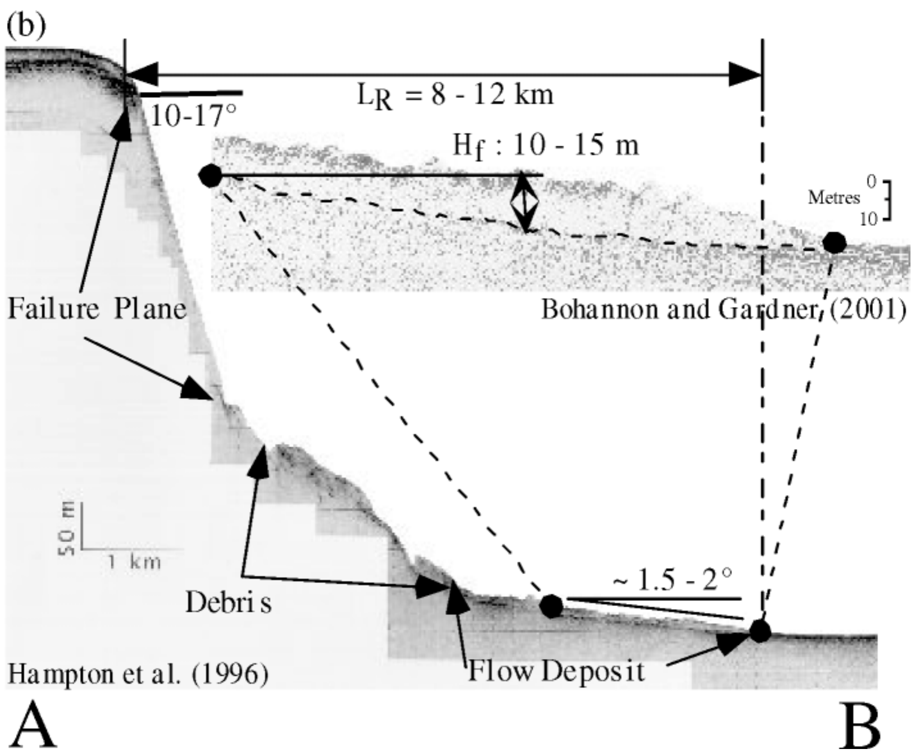
Although seismic and multibeam surveys can be carried out in a cost-effective manner, sampling and in situ testing are not as easy and are often much more costly for the same level of quality. Except for cases involving offshore resources such as oil and gas, in most situations sampling of sediments is done by means of gravity methods such as the following: Calypso (up to 60 m, mounted aboard the *Marion Dufresnes II*, Institute français de recherche pour l'exploitation de la mer (IFREMER)); Long Coring Facility (up to 30 m, Geoscience Atlantic, Canada) which is similar to the Jumbo Piston Corer (JPC) of the University of Rhode Island (Silva et al. 1999); Lehigh (up to 3 m); Kastin corer (up to 3 m); and box corer (0.6 m) and surface sampler (Shipek, VanVeen). The best coring method for sediments, in terms of geotechnical sample quality, is the box corer, but it has a very limited penetration. All other methods have their intrinsic difficulties mainly related to the partial remoulding of the soil during the penetration in the sediment and the presence of gas. For the case of gas hydrates, gas hydrate autoclave coring equipment (HYACE) is being developed by a European consortium composed of the Technical University of Berlin, the Ocean Drilling Program (ODP), and GEOTEK (U.K.). The proposed technology will maintain the sample under pressure while various nondestructive geophysical testing methods are used. For rock sampling or very stiff sediments, techniques developed by the ODP are good but very expensive and usually out of reach for most studies. A recent drilling tool, called the portable remotely operated drill (PROD, Benthic GeoTech, Australia), has been designed to drill into about 10–100 m of sediments or rock in water depths up to 2500 m. Its only limitation, from a geotechnical viewpoint, is the size of the core barrel (6 cm).

In situ testing and direct observations

Core quality is still a major issue in geotechnical investigations of submarine slides, particularly at sites where gas content is high enough to produce significant disturbance of the sample, often once it is on the ship's deck. In addition to samples, information required on pore pressures can be made via in situ techniques that have been developed for general purposes but can be used in submarine landslide investigations. The Lancelot and Excalibur probes were designed as a piezocone, which can also collect gas samples (Christian et al. 1993, 1994). A similar probe, called PUPPI (pop up pore pressure instrument) has been developed to measure pore pressure in sediments (Schultheiss 1990). IFREMER has also developed a falling cone penetrometer (PENFELD). All of these are gravity methods and their maximum penetration depth is less than 10 m.

Fig. 4. Palos Verdes rock avalanche. (*a*) Oblique view, showing the extent of the slide debris, the possible extension of the instability towards the northwest (shown at X), and signs of instability as indicated by potential fissures. (*b*) Seismic line, indicated in (*a*), which shows the nature of the debris and the characteristics of the run-out zone (seismic lines are modified from Hampton et al. 1996 and Bohannon and Gardner 2001). H_f, height of the debris flow; L_R, run-out distance.

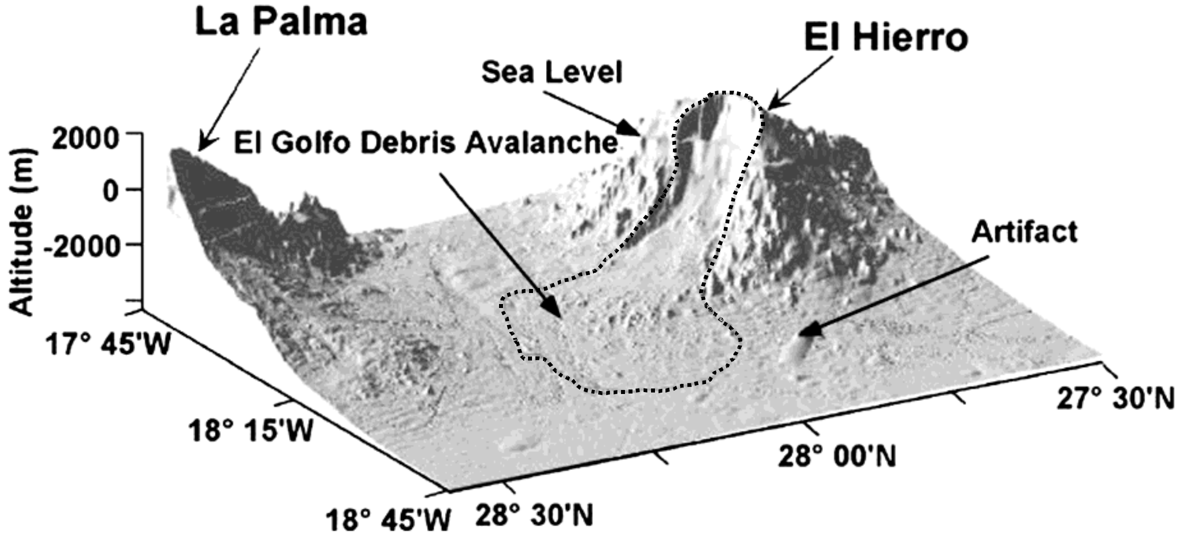




In situ observations can also be made using remotely operated vehicles (ROV). We do not have the space here to provide details on these techniques, but we can mention two examples, namely the VICTOR operated par IFREMER (France) or the ROPOS operated by a Canadian consortium of universities. This heavy equipment can be used to provide direct observations of the large-scale morphology, collect samples of water or sediments, or push instruments inside the sediment (usually less than 1 m).

As seen from the previous discussion, although our capacity to obtain in situ measurements has greatly improved recently, our coring and sampling techniques are lagging behind the

Fig. 5. El Golfo debris avalanche off El Hierro Island (Canary Islands, Spain; Urgeles et al. 1997), and the western tip of the Cumbra Nueva debris avalanche in La Palma on the left side of the image.



technological development of multibeam surveys. Since in most geotechnical investigations, the weakest component is the sample, greater efforts should be made, at least for sediments, to improve the sampling quality and sample conservation, particularly for gassy sediments.

Mechanics of submarine landslide initiation: prefailure and failure stages

Because of the recent development of HRS and multibeam surveys, it is now possible to investigate in detail slope morphology in search of revealing factors of the prefailure stage of a slope. Such elements consist of deformation or creep near or on the slope which are evidenced by the presence of fissures or depressions near the crest or in the slope, as has been shown for the Palos Verdes rock avalanche (Locat et al. 2001) (Fig. 4) and along the margin off the coast of Virginia and North Carolina (Driscoll et al. 2000). Abnormal fluid conditions in the slope region are also evidenced by the presence of seeps, mounds, and vents.

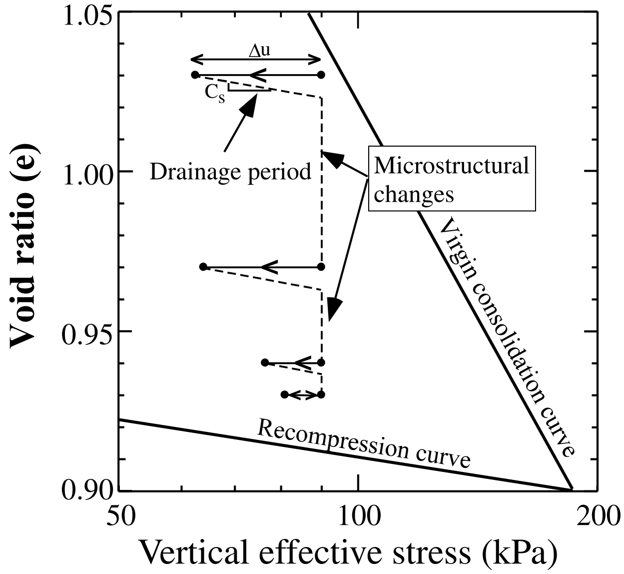
The failure stage results from various causes (see Fig. 1*a*). Researchers have specified many possible triggers for the initiation of submarine landslides, including (*i*) oversteepening, (*ii*) seismic loading, (*iii*) storm-wave loading, (*iv*) rapid accumulation and underconsolidation, (*v*) gas charging, (*vi*) gas hydrate disassociation, (*vii*) low tides, (*viii*) seepage, (*ix*) glacial loading, and (*x*) volcanic island growth.

Seismic loading and oversteepening were considered in the early work of Morgenstern (1967), and many submarine landslide initiation prediction procedures have focused on these triggers ever since (e.g., Lee et al. 2000). However, work on recent sediments of the Eel River margin (Boulanger et al. 1998; Boulanger 2000) has shown that repeated, nonfailure, seismic events can actually strengthen the sediment column through development of excess pore-water pressures during earthquakes and subsequent drainage, resulting in a densification during intervening periods. This was observed from a series of cyclic loading – drainage tests on normally consolidated specimens carried out with a cyclic simple shear test apparatus. An example of the test results is given in Fig. 6 for an initially normally consolidated reconstituted specimen. Here, the sediment begins to exhibit overconsolidation and a significant strength increase if a period of drainage is allowed between repeated earthquake simulations. The specimen shows a decrease in the void ratio and an increasing shearing resistance to liquefaction after each cycle. We propose calling this buildup of shearing resistance “seismic strengthening” and suggest that this mechanism partly explains the paucity of shallow submarine landslides on the Eel River margin, the most seismically active margin in the continental United States, and possibly in other areas with similar sediment and tectonic settings.

Storm-wave loading and underconsolidation (or the presence of weak layers) became recognised as major factors in causing submarine landslides following the failure of or damage to several offshore drilling platforms when Hurricane Camille struck the Mississippi Delta in 1969 (Bea et al. 1983).

Further work (e.g., Whelan et al. 1977; Hampton et al. 1982) showed that bubble-phase gas charging can degrade sediment shear strength and contribute to slope failure. Other studies (e.g., Kvenvolden and McMenamin 1980) have shown the existence of gas hydrates underlying many submarine slopes. Such hydrates are ice-like substances, consisting of natural gas and water, which are stable under certain pressure and temperature conditions that are common on the sea floor (Fig. 7). When temperature increases or pressure decreases, the stability field changes and some of the hydrate may disassociate and release bubble-phase natural gas. Unless pore-water flow can occur readily, this gas charging leads to excess pore pressures and degraded slope stability. Kayen and Lee (1991) suggested that worldwide lowering of sea level during glacial cycles could lead to numerous slope failures because of gas hydrate disassociation. A well-known case is the Storegga slide off the coast of Norway (Fig. 8), which is one of the largest submarine landslides, and other examples include those found along the northwest African margin (Embley 1976, 1982; Embley et al. 1978; Masson et al. 1992, 1993, 1998; Weaver et al. 2000). The Storegga slide was

Fig. 6. Effects on void ratio of only a few cycles of cyclic loading and drainage (Boulanger et al. 1998; Boulanger 2000). C_s, swelling coefficient; Δu, excess pore pressure.



probably triggered by a process involving gas hydrates (Bouriak et al. 2000) about 8000 years ago, involved a total volume of nearly 5000 km^3, and travelled from the western coast of Norway to the south of Iceland (Harbitz 1992). Of more immediate interest, warming of the sea floor through changes in major current flow patterns in the oceans or global warming could potentially cause similar effects. The impact of oil and gas offshore production in areas where gas hydrates are present poses difficult questions regarding the effect of these activities on the stability of gas hydrates and the link between gas hydrates and slope instability or the potential reactivation of older mass movements.

Coastal landslides are probably those which can be more easily linked to human activities (e.g., construction and dredging). They frequently occur during low tides through a mechanism similar to that of the rapid draw-down condition in earth dams, i.e., the pore pressure in the subaerial part of the delta does not have time to reach steady state conditions for the groundwater flow. Failure can also be induced by increased pore pressures due to construction, as has been speculated for the case of the Nice Airport (Mulder et al. 1993) and Skagway, Alaska (Cornforth and Lowell 1996; Kulikov et al. 1996, 1998), failures. The Kitimat Arm failure (Prior et al. 1982), which occurred in British Columbia in 1975, is another example of such a mechanism.

Some coastal slides have been associated with blasting for road construction (Kristiansen 1986). As part of the ADFEX project, blast-induced liquefaction experiments were attempted both in Norway (By et al. 1990) and in Lake Melville, Labrador (Fig. 9) (Couture et al. 1995). At Lake Melville, the Kenamu River delta was partly destabilized by the blasting of a 1200 kg charge of explosives, but the in situ conditions (gas-charged sediments and local morphology) interfered with the transfer of the blast energy and thus limited the extent of liquefaction and flow failure in the sandy sediments (Couture et al. 1995).

Seepage can occur beyond the immediate coastline through coastal aquifers (Robb 1984) and other pore fluid migration processes, including sediment subduction at plate boundaries (Paull et al. 1990; Orange and Breen 1992). Under appropriate conditions, such seepage can lead to failure and potentially to the ultimate development of submarine canyons (Orange et al. 1997).

Continental glaciations may have played a significant role in inducing landslides (Mulder and Moran 1995). Factors that may be important include loading and flexing of the crust, greatly altered drainage and groundwater seepage, rapid sedimentation of low-plasticity silts, and rapid emplacement of moraines and tills over soft hemipelagic interstadial sediments. A particularly dense set of large submarine failures off the coast of New England (O'Leary 1993) may be related in part to nearby continental glaciations.

The buildup associated with volcanic islands constitutes an environment within which submarine mass movements are extremely common and among the largest mass movement features on the surface of the Earth (Moore and Normark 1994; Holcomb and Searle 1991; Voight and Elsworth 1997; Masson et al. 1998). Giant slumps that can produce earthquakes of magnitude 7 or greater, as they deform (Lipman et al. 1985), or which could have resulted from them can also generate debris avalanches with run-out distances in excess of 200 km (Moore and Normark 1994). The extent of these features has only been recognised since the development of long-range side-scan sonar devices like GLORIA. The immediate hazard to volcanic islands from failures such as these is clear, as is the hazard to more distant locations through the production of tsunamis. The cause of the failures is not well understood, although it must be related in part to the presence of magma near the failure surfaces, the physical properties of rapidly emplaced volcanic rock, and magma or gas pressures within the core of the islands (Masson et al. 1998). A challenge to submarine landslide research is to determine how these giant slumps could convert to catastrophic debris avalanches and to evaluate the likelihood of any giant landslide activity with a time frame that is relevant to present coastal and island populations.

In recent years, major triggering mechanisms have been invoked as significant in producing large submarine mass movements. This is particularly the case for the role of gas hydrates and weak layers. The exact hazard posed by gas hydrates and volcanic island build up, as triggers for submarine mass movements, remains a major challenge for future research.

Mechanics of submarine landslide mobility: post-failure stage

Following initial failure, some landslides mobilize into flows, whereas others remain as limited deformation slides or slumps (Hampton et al. 1996). The mechanisms for mobilization into flows are not well understood but at least one factor is likely the initial density state of the sediment (Poulos et al. 1985; Lee et al. 1991). If the sediment is less dense than that in an appropriate steady state condition (contractive sediment), it appears to be more likely to flow than sediment that is denser than that in the steady state condition. The ability to flow may also be related to the amount

Fig. 7. The role of gas hydrates on slope instability development as a result of sea level lowering. (*a*) Time of high sea level with the base of solid gas hydrates close to the surface of the sediments. (*b*) Lower sea level resulting in reduction in confining pressure and release of gas hydrates. (*c*) Solid gas hydrates in sediments (ice-like crystals). Scale in centimetres.

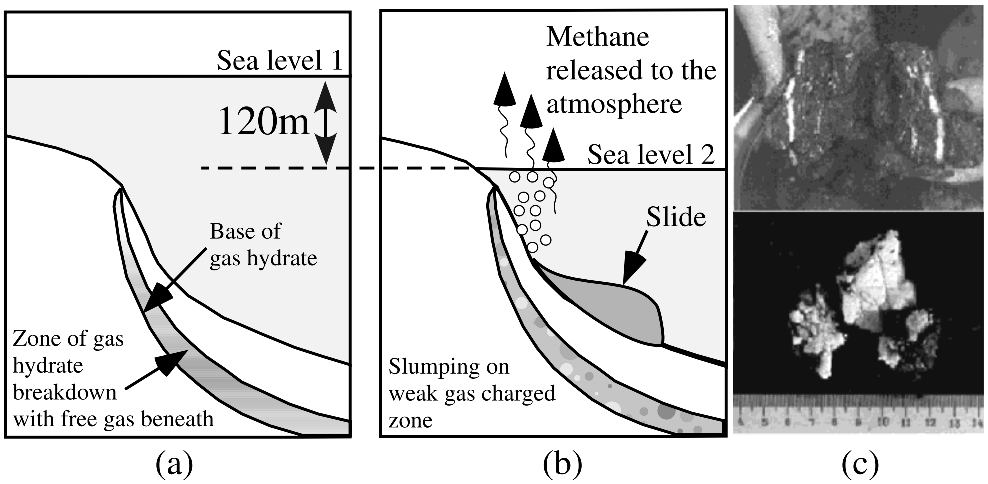
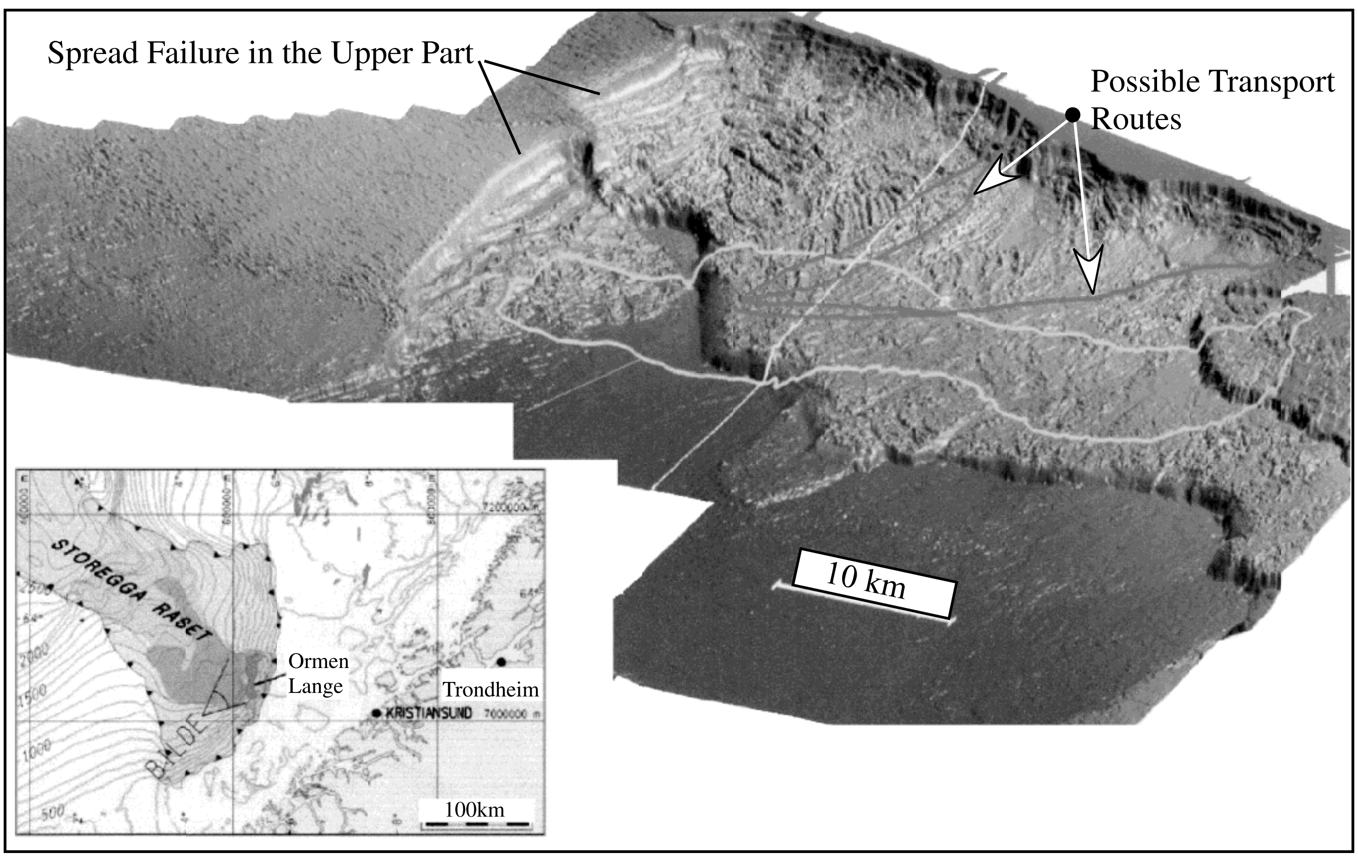


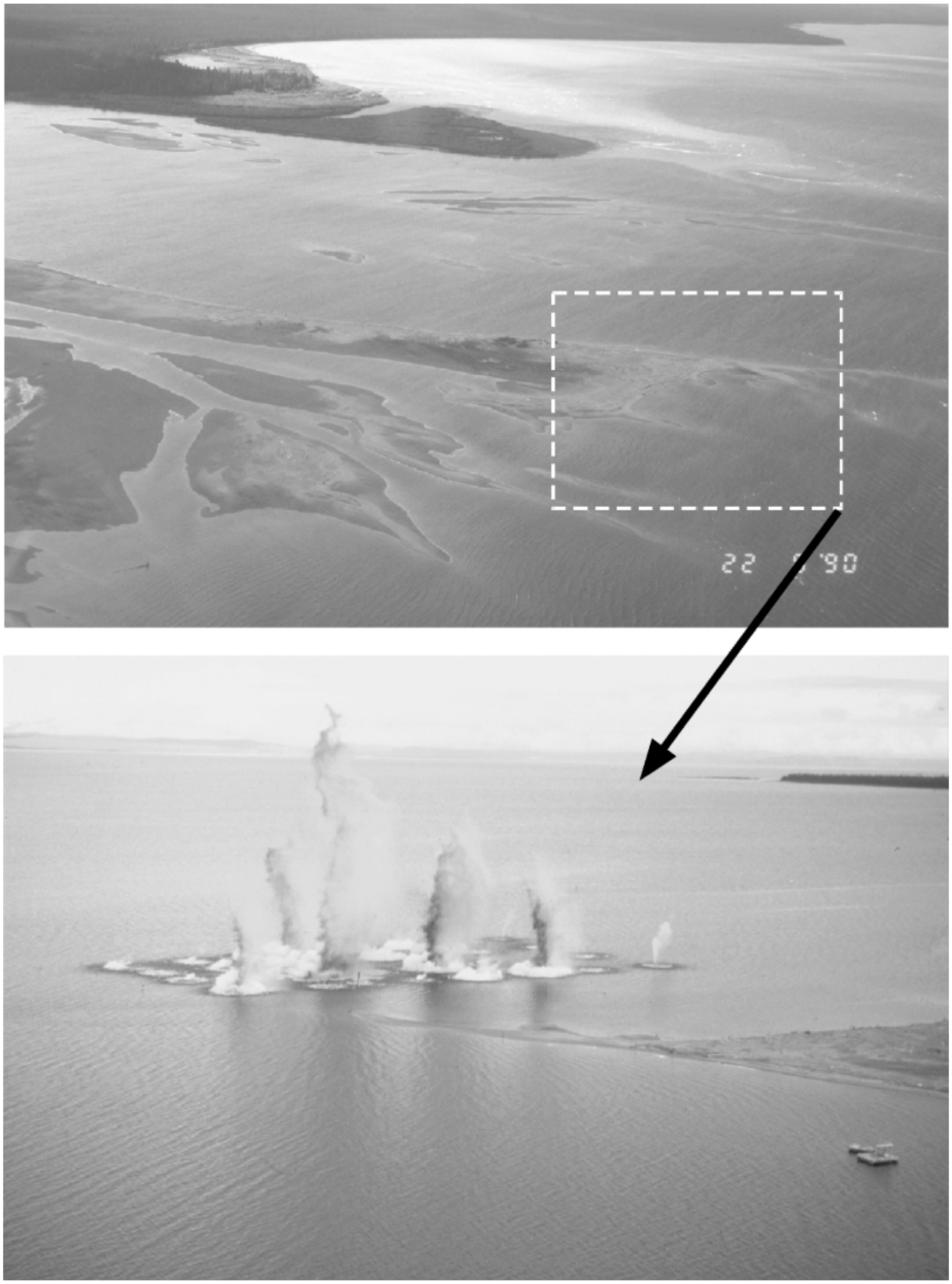
Fig. 8. A 3D view of the Storegga slide off the coast of Norway. The slide extends on the sea floor over a distance of more than 160 km (source: Norsk Hydro/NGI/Statoil). The insert shows the overall extent of the Storegga slide in the source region. Bathymetric contours in metres.



of energy transferred to the failing sediment during the failure event (Leroueil et al. 1996).

In considering the mobility of a mass movement (Fig. 10), we can distinguish between two components: the retrogression (R) and the run-out distance (L). Heim (1932) first proposed looking at the mobility of a given mass involved in a landslide in terms of the geometry of the deposits before and after the slide event and proposed the use of the term Farboschung ($F = \Delta H/L$), where ΔH is the elevation difference between the crest of the slide and the tip of the debris, which represents the angle of the line joining the escarpment to the maximum distance reached by the debris. The Farboschung is commonly used to characterize the mobility of a mass movement. In such a definition, the term L would

Fig. 9. Attempts to generate a submarine slide and debris flow at the Kenamu River delta, Lake Melville, October 1991. (*a*) Oblique view of the Kenamu delta, with the study area outlined. (*b*) Blasting of sediments using 1200 kg of explosives.



also include R, with L^* taking into account the pre-slide topography. For slides in sensitive clays, R has been related to the ratio $C_u/\gamma H$ (Mitchell and Markell 1974), where C_u is the undrained shear strength, and γ is the bulk unit weight. The parameter R has also been linked to the liquidity index (I_L) by Lebuis et al. (1983). Although not well constrained in the case of submarine landslides, R becomes negligible for long travel distances but still remains a critical element for the safe positioning of sea-floor structures.

Heim (1932) observed that for subaerial slides, F was inversely proportional to the initial volume (V) of the sliding mass. Edgers and Karlsrud (1982) reviewed the extent of submarine slides and compiled data on values of F and V for submarine landslides which have been updated by Hampton et al. (1996). Figure 11 does not distinguish channelized flows, which would tend to provide much greater run-out distances. In comparison with subaerial slides, submarine landslides are much more mobile and tend to involve larger volumes (Fig. 11).

Fig. 10. Geometrical description of mobility. h, flow thickness; h_i, initial height; β, slope angle.

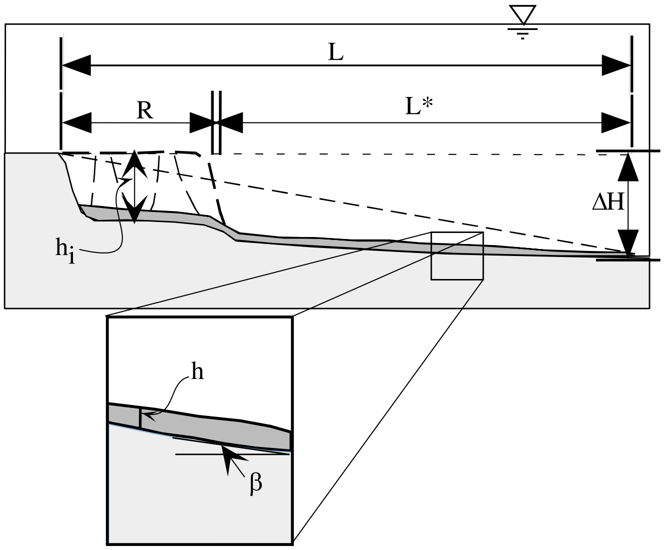
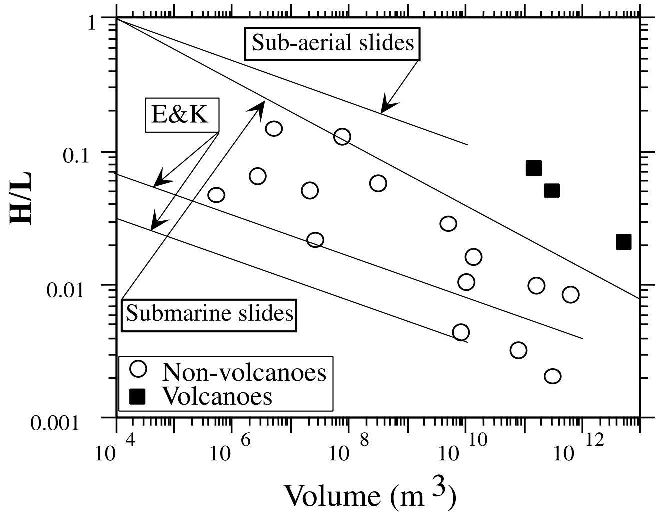


Fig. 11. Mobility of submarine mass movements as a function of the ratio H/L and volume (E&K, Edgers and Karlsrud 1982; see Hampton et al. 1996 for landslide data).



The relationship F versus V results directly from the transformation of the potential energy (E_p) of a given mass into other forms of energy, including kinetic energy (E_k):

$$[1] \qquad E_p + E_s = E_k + E_f + E_D + E_v + E_r$$

where E_s is the seismic energy resulting from an earthquake, E_f is the friction loss, E_D is the friction loss due to drag effects on the upper surface of the flow, E_v is the loss due to viscous effects, and E_r is the energy used to remould or transform the intact material. During the course of a submarine slide event (or also a subaerial slide), there appears to be a process by which there are some changes in the ratio of solids to water which provide a sufficiently low strength to allow flow to take place (see also Fig. 1*b*). Whatever the exact nature of the phenomenon, it is embedded here in the remoulding energy (E_r). Many hypotheses are proposed to explain the development of flows, including the following: (*i*) it must take place at the time of, or soon after, failure; (*ii*) the transformation of the original mass can result from fragmentation associated with intercollision in rock masses (Leroueil et al. 1996; Davies et al. 2000); and (*iii*) it may include the effects of impact with the sea floor of the rock mass (e.g., chalk along the coast of England; Hutchinson 1988) or sediments (Flon 1982; Tavenas et al. 1983).

Similarly, to explain far-reaching debris flows reported by Schwab et al. (1996), Locat et al. (1996) invoked a significant loss in strength of the soil mass in the starting zone to account for the very low remoulded shear strength required for the observed mobility (up to 400 km; Fig. 12).

Possible boundary conditions during a flow event are illustrated in Fig. 13. As for snow avalanches (Norem et al. 1990), the flowing material is divided into two components: dense and suspension flows. The dense flow could be a rock avalanche, debris flow, or mudflow. The suspension flow, which is generated by the drag forces acting on the upper surface of the dense flow, will remain as a turbidity current once the dense flow stops or moves slower than the suspension flow. This phenomenon can take place on slopes as low as 0.1° (Schwab et al. 1996). Recently, Mohrig et al. (1999) have shown that once a critical velocity is reached, around 5–6 m/s, hydroplaning could also induce added mobility by reducing the shearing resistance at the base of the frontal part of the flowing mass (Fig. 13). This process of hydroplaning is similar to what has been observed by Laval et al. (1988) for density surges and turbidity currents. This process will tend to lift the frontal portion of the dense flow, thus reducing the shearing resistance at the interface with the underlying immobile layer. One aspect that is not yet taken into account by the physical modelling of hydroplaning debris flows is the stretching of the flowing mass resulting from higher velocities in the frontal part which could lead to a segmentation (or partitioning) of the debris.

During the flow, we should expect some erosion or sedimentation to take place, but these phenomena still remain to be described more fully and integrated into numerical models. In some environments, e.g., the Gulf of Mexico, the flow will be channelized and, if the channel is filled and the flow height is in excess of the critical flow height, flow can proceed over long distances (Johnson 1970).

Once a mudflow or a debris flow is generated, the velocity of the flowing mass is such that the flowing material remains under undrained conditions. In such a case, and considering the high rate of movement, the phenomenon is best described by means of fluid mechanics rather than soil mechanics. In the case of mudflows or muddy debris flows, the flow behaviour can be represented by the following three types of fluids (Locat 1997), including a Bingham fluid (see also Johnson 1970; Huang and Garcia 1999)

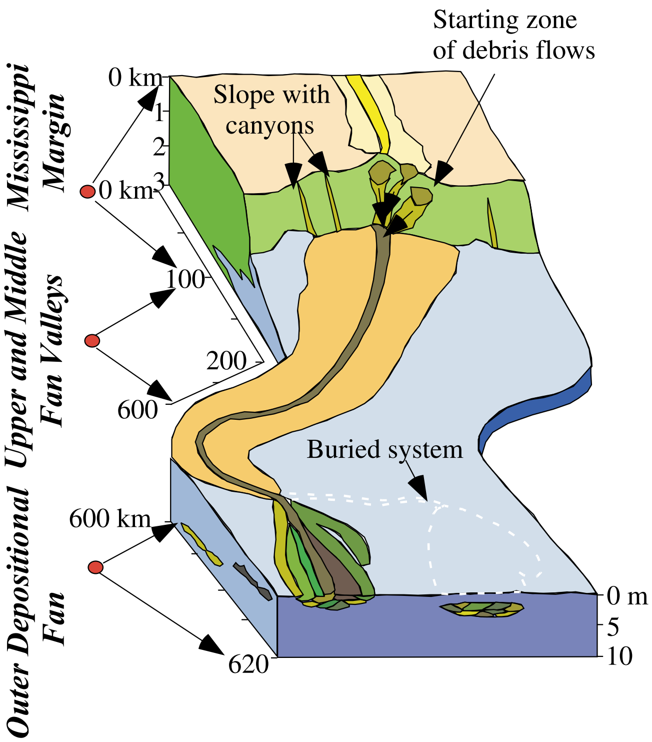
$$[2] \qquad \tau = \tau_c + \eta\gamma^n$$

a Herschel-Bulkley fluid (see also Coussot and Piau 1994)

$$[3] \qquad (\tau - \tau_c) = K\gamma^n$$

and a bilinear fluid (see also O'Brien and Julien 1988)

Fig. 12. Schematic view of far-reaching debris flows deposited on the Mississippi Fan (modified after Twichell et al. 1991).



[4] $$\tau = \tau_c + \eta\gamma + \left(\frac{c}{\gamma + \gamma_0}\right)$$

where τ is the resistance to flow, τ_c is the yield strength, η is the dynamic viscosity (in mPa·s), γ is the shear rate (not to be confused here with the unit weight in soil mechanics), γ_0 is the shear rate corresponding to the yield strength of the bilinear fluid, and c is a constant with units in kPa·s^{-1}. K (in mPa·s) is equivalent to the viscosity once the mixture is analysed as a non-yield-stress fluid using eqs. [2] and [3]. The exponent n qualifies the state of the mixture as pseudo-plastic for $n < 1$, as a dilatant fluid for $n > 1$, and as a Bingham fluid for $n = 1$. The bilinear model has been successfully tested against experimental data and provides a good prediction of the movements in the run-out zone (Imran et al. 2001).

In addition to the rheological models, Norem et al. (1990) proposed analysing the mobility of submarine mass movements by using a viscoplastic model described by

[5] $$\tau = \tau_c + \sigma(1 - r_u)\tan\phi' + \eta\gamma^n$$

where σ is the total stress, r_u is the pore-pressure ratio ($u/\gamma h$, where u is the pore pressure and h is the flow thickness), and ϕ' is the friction angle. This constitutive equation is a sort of hybrid model, similar to what has been proposed by Suhayada and Prior (1978). The first and third terms of the equation are related to the viscous components of the flow, as in eqs. [2]–[4]. The second term is a plasticity term described by the effective stress and the friction angle. An interesting aspect of such an approach is that it can be adjusted to various flow conditions. For example, if we consider a rapidly (undrained) flowing granular flow, we would be mostly using the third term of eq. [5] with a value of n greater than 1. In the case of a mudflow (undrained), terms one and two of eq. [5] would be used, but the value of n would be less than or equal to 1. For flows where the velocity and the material properties are such that excess pore pressures can dissipate, the second term could dominate and the equation would approach the sliding-consolidation model proposed by Hutchinson (1986). For rock avalanches, the last two terms of eq. [5] would be considered.

In many cases, we consider the mixture as a yield stress fluid, so the rheological behaviour of the matrix can be represented by a yield strength and a viscosity parameter. It has been proposed that the yield strength and viscosity could be related to the liquidity index (I_L) (Locat and Demers 1988; Locat 1997) for as long as the liquidity index is greater than 0 (i.e., for a water content above the plastic limit). Results obtained for various soils or sediments are given in Fig. 14. The results are partly influenced by the floc size and by salinity in the case of the yield strength (Locat 1997). Nevertheless, for a single sediment or soil, the quality of the relationship is quite reasonable. An interesting observation, obtained from laboratory testing, is that the yield strength contributes about 1000 times more than the viscosity to the resistance to flow of the fluid. The results in Fig. 14 can be used hereafter to provide a first approximation of the relationships between liquidity index and rheological parameters (see also Locat 1997):

[6] $$\eta = \left(\frac{9.27}{I_L}\right)^{3.3}$$

[7] $$\tau_c = \left(\frac{5.81}{I_L}\right)^{4.55}$$

for a pore-water salinity of about 0 g/L;

[8] $$\tau_c = \left(\frac{12.05}{I_L}\right)^{3.13}$$

for a pore-water salinity of about 30 g/L; and

[9] $$\eta = 0.52\tau_c^{1.12}$$

where η is in mPa·s and τ in Pa.

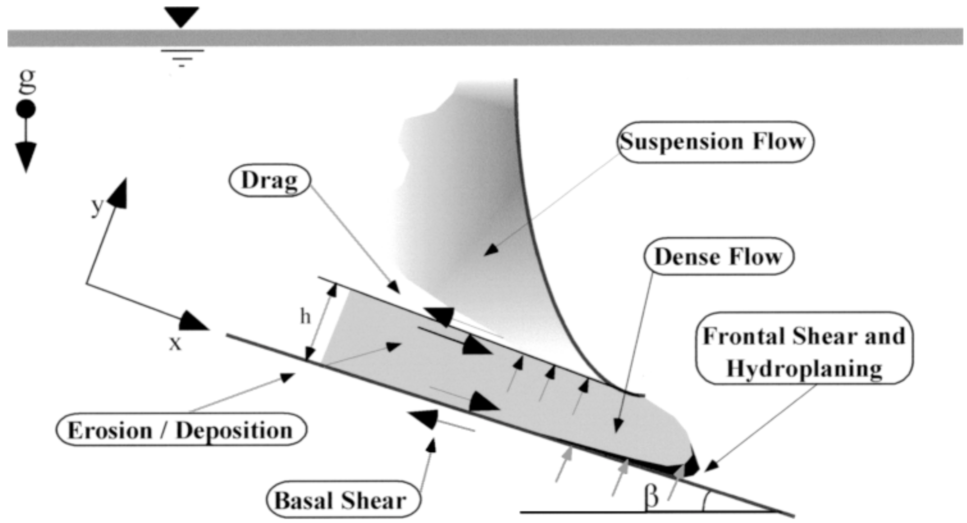
Recently, these relationships have been used successfully by Elverhoi et al. (1997) to analyse the behaviour of debris flows along the coast of Norway. For mudflows or matrix-controlled debris flows, Hampton (1972) has shown that the minimum thickness of the flowing material (H_c, in m) for flow to take place can be defined by the following relationship:

[10] $$H_c = \left(\frac{\tau_c}{\gamma' \sin\beta}\right)$$

where γ' is the submerged unit weight in kN/m^3 (not to be confused here with the shear rate in fluid mechanics), and β is the slope angle (note that τ_c is given in kPa). Modifying eq. [8], for seawater, and considering τ_c in kPa,

[11] $$\tau_c = 2.42\, I_L^{-3.13}$$

Fig. 13. Schematic diagram showing the generation of a turbidity current (suspension flow) for drag forces on the surface, potential lifting of frontal lobe leading to the process of hydroplaning, the basal shear stress causing erosion, and deposition. *g*, acceleration due to gravity.



we can rewrite eq. [10] partly as a function of the liquidity index:

$$[12] \qquad H_c = \frac{2.42 I_L^{-3.13}}{(\gamma - \gamma_w)\sin\beta}$$

where γ and γ_w are the total unit weight of the sediment and water, respectively. Equation [12] is a generalization of the approach already proposed by Schwab et al. (1996) for debris flows in the Gulf of Mexico to estimate the critical flow height from easily determined physical parameters. In eq. [12], all parameters can be obtained easily from cores and even on remoulded samples, so the liquidity index can be measured easily as can the bulk density (often obtained from multisensor track (MST) logging).

The liquidity index – yield strength relationship can also be used to back-calculate the yield strength of a debris flow at the time of the event for as long as the water content of the clast is greater than that for the matrix (Fig. 15). This assumes that no consolidation of the clast took place since deposition. Such an approach, based on the work of Hampton (1975), has been used successfully by Schwab et al. (1996) to analyse the mobility of debris flows on the Mississippi Fan. Hampton (1975) considers the mixture like a Bingham fluid, so the largest diameter of the clast (D_{max}) which can be supported by the clay–water slurry is calculated using the following relationship:

$$[13] \qquad D_{max} = \frac{8.8\tau_c}{g(\gamma'_c - \gamma'_m)}$$

where g is the acceleration due to gravity; and γ'_c and γ'_m are the submerged unit weights of the clast and the matrix, respectively (adapted from Schwab et al. 1996). The use of eq. [13] could also be another way of estimating the liquidity index, at the time of the mudflow event, using eqs. [7] and [8].

Coupling many of the above relationships, we analysed muddy, clayey sediments containing clay clasts to develop a chart that can be used to restrain the approximation of the rheological parameters at the time of the mudflow event. This is illustrated by the results displayed in Fig. 15 for sediments from the Black Sea, with their physical properties as indicated in the figure caption. We have represented the two extreme curves (upper and lower) relating the liquidity index and the yield strength (from eqs. [7] and [8]) which provide a realistic range of values for both liquidity index and yield strength. Also shown in Fig. 15 is the computation of eq. [13] for different values of D_{max} (here given in centimetres). For example, if the maximum observed clast diameter is 10 cm (with physical properties as indicated in the figure caption), the only possible ranges of liquidity index and yield strength values of the matrix would have to fall inside the area bounded by the so-called upper and lower curves. Moreover, if for a given sediment the relationship between I_L and τ_c has been obtained directly using a viscometer, then the potential range of values can be greatly reduced. The end result can be quite useful in trying to determine the rheological conditions under which a mudflow or a debris flow has taken place (provided that the water content of the clast has not changed since deposition, or could be estimated properly).

We have shown that it is possible, at least for sediments, to analyse the mobility of sediments and obtain, or estimate from the liquidity index, the various parameters necessary for using the various flow models. One of the key question here, which is also true for on-land mass movements, is how does the material acquire these physical (rheological) properties? For example, Locat et al. (1996) indicated that the mobilized yield strength (or remoulded shear strength) back-calculated for the Gulf of Mexico debris flows was up to three orders of magnitude lower than the minimum remoulded shear strength measured in the potential source area today. There must be some mechanical processes taking place during the transition from failure to post-failure which generate significant volumes of a mixture having a very low remoulded shear strength. This transition phase from slide to flow, which can be accompanied with some acceleration of the moving mass,

Fig. 14. Using the liquidity index (I_L) to estimate the rheological parameters of mudflows or the muddy matrix of debris flows (note that water, at 20°C, has a viscosity of 1 mPa·s). Samples S-100 and S-450 indicate sediments from the Eel River margin, California.

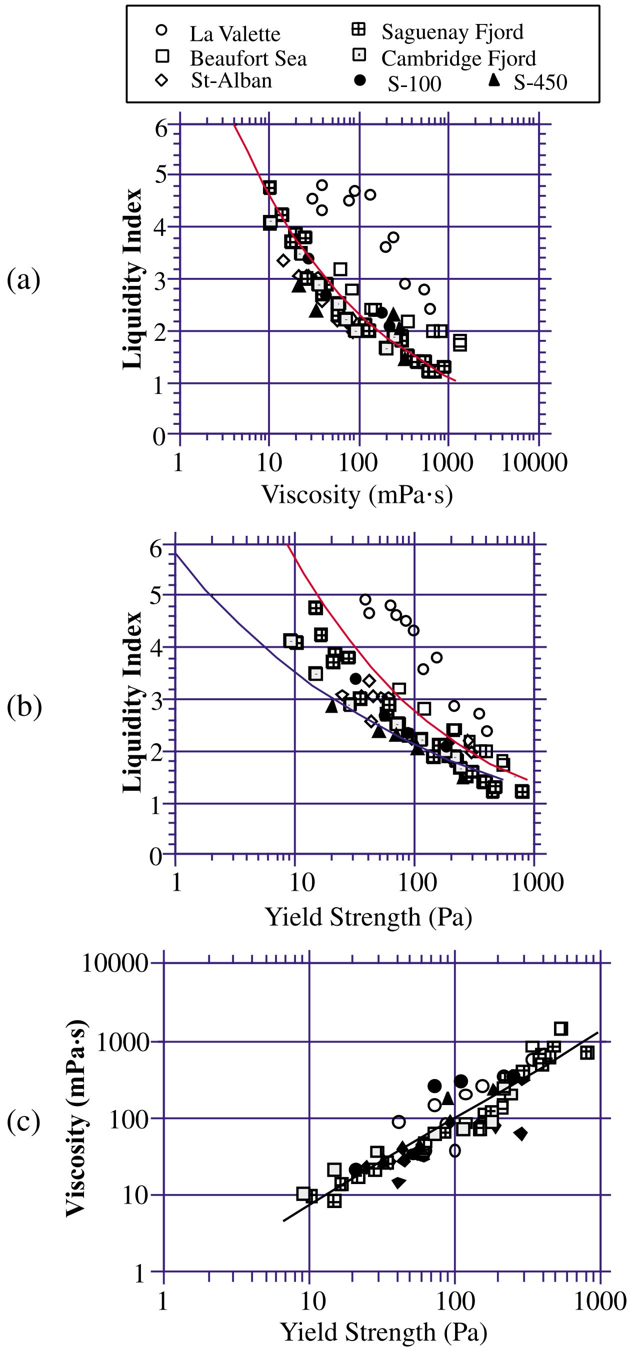
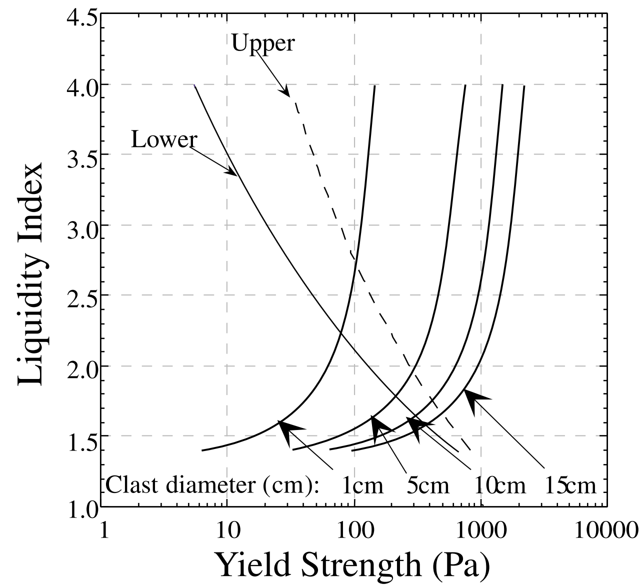


Fig. 15. Using the liquidity index – yield strength relationship to estimate rheological properties at the time of debris flow formation. Index properties of the soil tested for this computation are as follows: plastic limit w_p = 56%, liquid limit w_L = 183%, and grain density G_s = 2.7 for the matrix; natural water content w_n = 230% for the clast.



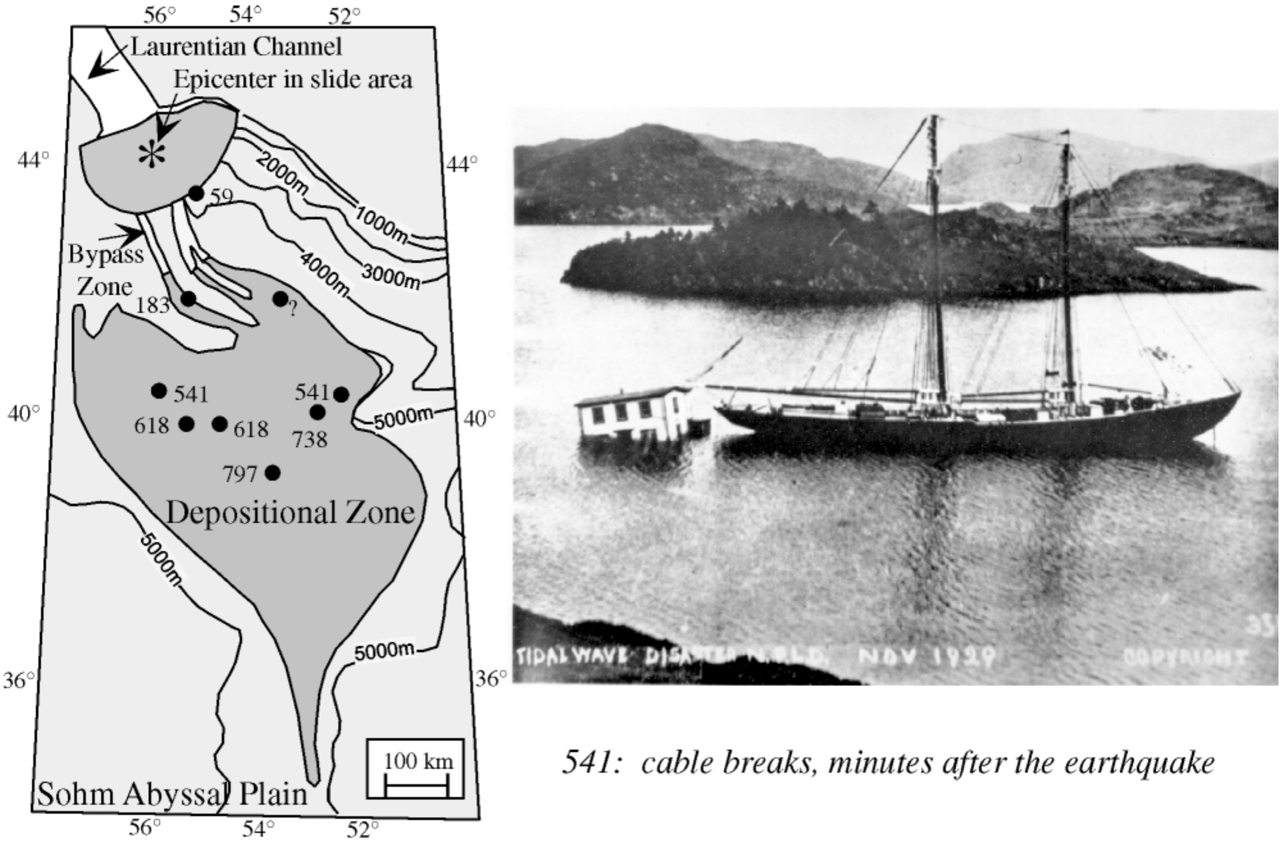
is also critical for the generation of tsunami (Locat et al. 2001). The case of submarine rock avalanches is of the same nature, as we do not yet understand how the failure mechanism can generate the very large propagation as observed, for example, with the Hawaiian submarine rock avalanches (Moore et al. 1992). Therefore, we see this aspect of transition from slide to flow as one of the major challenges ahead in the study of submarine mass movements.

The foregoing analysis of submarine mass movements indicates that these phenomena are as diversified as their counterparts on land, that they can be very mobile, and that they involve very large volumes of material moving at significant velocities. By its own nature, the marine environment is not easily accessible, particularly for achieving a detailed description of the material involved. Therefore, the complexity of the submarine mass movements and their geotechnical characterization will have to be taken into account for hazard and risk assessment.

Hazard and risk assessment

Evaluating the risk posed by submarine landslides and predicting the regional variation of future landslide events is in its infancy. The main questions raised about the hazard are as follows: (*i*) where did mass movement occur and where will it occur? (*ii*) how frequently will mass movement occur? (*iii*) what are the triggering mechanism(s)? (*iv*) what is the area of influence of mass movement? and (*v*) can a previous failure be reactivated? These questions are similar to those asked about subaerial mass movements, but our actual knowledge of submarine landslide risk assessment is far from what has been already achieved for on-land landslide risk assessment (Cruden and Fell 1997; Leroueil and Locat 1998). As shown in the paper, the extent of submarine mass movement can be well documented and some initial attempts (see later in the paper) are being made to predict the potential for landsliding on a regional scale. The other elements of the problem are not at all well constrained at the moment. The case of the Grand Banks slide (Piper et al. 1988) provides a good example to illustrate the various components that must be taken into account for a proper risk assessment (Fig. 16). The 1929 Grand Banks earthquake triggered a major submarine slide that transformed into a debris flow travelling over a distance of not more than 80 km (Locat et al.

Fig. 16. This sketch is adapted from Piper et al. (1985), who illustrated the extent of the Grand Banks slide of 1929. Note that the total travel distance affected by the slide and the resulting turbidity current extend as far as 1000 km from the epicentre. The water depth range is from about 1000 to 5000 m. The total event lasted more than 12 h. ●, cable breaks (the numbers indicate minutes after the earthquake). The mass movement generated a tsunami that destroyed part of a village, killing 27 people. The photograph shows a schooner towing a house that had been washed out to sea during the tsunami (photograph courtesy of A. Ruffman).



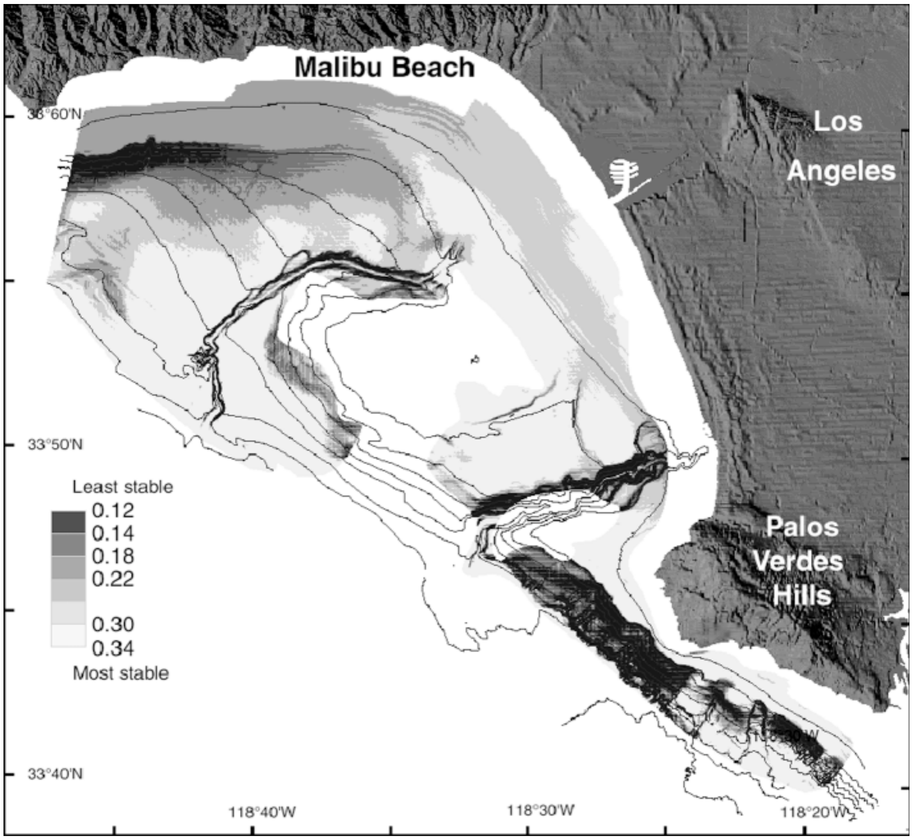
1990). The debris flow initiated a turbidity current that covered a distance of at least 1000 km. Data from cable breaks were used to indicate that the initial velocity was as high as 25 m/s and that it was still about 5 m/s at a distance of more than 500 km from the starting zone. In addition, the slide generated a 20 m tsunami wave that moved toward the coast of Newfoundland, killing 27 people (Piper et al. 1985, 1988).

The generation of the turbidity current is indicative of an initially rapid mass movement (Jiang and Leblond 1992). In addition, the observed cable breaks suggest that the flow was still able to generate damage even at a distance of nearly 1000 km from the source. It is difficult to know if the earthquake and the slide itself did reactivate older mass movements or how frequent such events could be. For the frequency component of the hazard evaluation, the answer is likely to be written in the sediments either as “seismites” (sediment layers resulting from earthquake-related sediment deposition; e.g., Perret et al. 1995) or as tsunami-related sediment deposits (Clague and Bobrowsky 1994). As shown in Perret et al. (1995), turbidites will have a characteristic textural and strength signature compared to bioturbated layers, which show a high variability of shear strength. Therefore, long cores of good quality are essential if one wishes to identify catastrophic layers which can than be dated or correlated to establish the submarine landslide hazards in a given area.

In terms of risk assessment, and apart from the work of Favre et al. (1992), little has been done about submarine landslides. The most recent activity has been a special workshop on seabed slope stability and its impact on oilfield drilling facilities (International Association of Oil and Gas Producers 1999). One sentence from this workshop report says it all: “No one understands how to cope with big or deep slides, except by avoiding areas prone to this type of behaviour.” This field is clearly new and requires methodological developments.

Referring to the statement cited in the previous paragraph, we would like to propose the use of the geotechnical characterization of mass movements detailed earlier (Leroueil et al. 1996). Lee et al. (2000) have made a step in that direction by incorporating a variety of regionally varying data into a geographic information system (GIS) to develop predictions of relative landslide susceptibility for two offshore areas, Santa Monica Bay in southern California and the Eel River margin in northern California. The map shown in Fig. 17 is produced by mapping the calculated values of the ratio of the critical horizontal earthquake acceleration (k_c) to the peak seismic acceleration with a 10% probability of exceedance in 50 years in the Los Angeles area. The approach requires detailed bathymetry and acoustic back-scatter information, such as are obtained from state-of-the-art multibeam systems. It also requires statistical information on loading functions, such as the

Fig. 17. Example of a regional map showing landslide susceptibility for the Los Angeles area, California, from integrated geotechnical and seismic databases. The units give the relative degree of stability, with the dark zone being the most unstable.



probability of particular seismic accelerations. An example of the latter is available for much of the United States margin (Frankel et al. 1996). Perhaps most significantly, information on sediment properties and state is needed along with the variability of both of these with subbottom depth.

Also desirable is the confidence one can place on this information, given measurement errors and the limited availability of samples and in situ measurements (see also Favre et al. 1992). Lee et al. (1999) deal with these requirements by mapping surface character using shallow sediment cores and then relying on normalized soil parameters (Lee and Edwards 1986) to define the response of the sediment to burial. Such an approach cannot be used to extrapolate to subbottom depths greater than a few metres and limits the approach to only shallow landslides. The approach also relies on infinite slope stability analysis and thus is incapable of handling complex geometries. Despite these limitations, the approach does provide an estimate of shallow landslide susceptibility that roughly mirrors the occurrence of such features on the margins investigated (Fig. 17). A challenge to extending this approach to other situations is to make better quantitative use of remotely sensed data and to incorporate more sophisticated slope stability analysis techniques using predictive models for shear strength and burial (Locat et al. 2002).

It is hoped that the development of better coring methods and the use of 3D seismic will be integrated, along with modelling of soil properties, in a general approach that would provide the variability and distribution of the necessary properties or parameters. This, along with the other available tools for both static and dynamic analysis (e.g., centrifuge testing; Phillips and Byrne 1995) of slope stability, will provide the necessary information to evaluate both the hazard and the risk assessment related to submarine mass movements.

Conclusions

This work was aimed at providing an overview of the achievements made since the early 1990s and presents some of the major challenges still ahead. When considering the intense research activities initiated over the last 5 years, a lot more could be said, and many fascinating problems remain. As a summary, our main conclusions on advances and challenges are presented here. They may not be complete because they reflect on our experience, which is more oriented towards the engineering aspects of submarine mass movements.

The major advances are as follows: (*i*) development of surveying techniques providing air photograph-like quality images of the sea floor; (*ii*) the development of high-resolution seismics relevant for the first 100 m of sediments; (*iii*) better understanding of the physics of rapid mass movements, including a description of post-failure behaviour, particularly for debris flows and mudflows; (*iv*) understanding of the generation of tsunami initiated by submarine mass movements; (*v*) determination of the rheological parameters and the use of the liquidity index; (*vi*) recognition of the role of gas hydrates in the development of slope instability; and (*vii*) introduction of the concept of hydroplaning to explain some of the large run-out distances achieved by debris flows or mudflows.

The major challenges are as follows: (*i*) improving sediment sampling and in situ measurement techniques; (*ii*) integrating 3D seismic methods into slope stability analysis; (*iii*) use of long cores to provide estimates of the frequency of catastrophic events in the aquatic environment; (*iv*) identifying and understanding the physical processes involved in the transition from failure to post-failure for a better prediction of the initial acceleration of the moving mass and the ongoing modifications of its physical properties leading to the acquisition of a fluid-like behaviour; (*v*) hazard assessment, particularly frequency and extent; (*vi*) monitoring the movement and mobilization of actual landslides; (*vii*) determining the role of subsurface water flow in initiating submarine landslides; (*vii*) integrating the role of gas hydrates in the analysis and prediction of submarine slope stability; (*viii*) evaluating the mechanics of giant submarine landslides and improving our understanding of the causes of their great run-out distances; and (*ix*) developing criteria to determine the cause of sea-floor deposits that have been described as either landslides or migrating sediment waves.

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