

Submarine Mass Movements and Their Consequences

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Introduction

In 1929, an earthquake off the Grand Banks of Newfoundland initiated a submarine mass movement that sheared undersea communication cables and generated a tsunami that resulted in deaths of 27 people along the south coast of Newfoundland. This event initiated the modern realization that the seafloor is a dynamic environment with potential to do harm. More recent catastrophic examples include submarine mass movements off the Nice airport in 1979 that removed part of the runway along with construction equipment and resulted in the loss of several construction workers (Dan et al. 2007; Kopf et al. this volume), and a 1998 event off Papua, New Guinea that caused a tsunami resulting in 2200 deaths (Tappin et al. 2001). On December 26, 2006, a submarine landslide in the Luzon Strait caused failure of undersea cables (Hsu et al. 2009), halting the entire internet network between Taiwan, Hong Kong, and China and affecting communications between Thailand, Malaysia, Vietnam, South Korea and Singapore for 12 h. Given that the combined GDP of Taiwan, Hong Kong and China approximates \$7.56 billion per day, the economic impact of this event was severe. As for the offshore hydrocarbon industry, aside from direct risk to exploration and production platforms, the Society for Underwater Technology estimates that the cost of damage to pipelines caused by submarine mass movements is about \$400 million annually.

As a result of instances like these and the potential economic and societal impact (an estimated 2.75 billion people worldwide live within 60 km of the coast), an interest in understanding the phenomenon of submarine mass movements has led to concerted efforts on behalf of governmental, non-governmental and international agencies to understand this risk to society, e.g. the United States Nuclear Regulatory Commission, the US National Tsunami Hazard Mitigation Program, the European and Canadian Continental Slope Stability (COSTA) Program, the Integrated Ocean Drilling Program and the joint United Nations Educational Scientific and Cultural Organization's (UNESCO) and International Union of Geosciences (IUGS) International Geosciences Program (IGCP) Project 511. The objective of IGCP project 511 is to bring a world-wide perspective to submarine mass movements and their consequences. This objective is realized by assembling

excellent contributions from active researchers, groups and institutions to provide diverse coverage of the many scientific and engineering aspects of this type of marine and coastal geohazard. To this end, this project has hosted four international symposia, the latest of which is represented by this volume. Previous symposia resulted in two books (Lykousis et al. 2007; Locat and Meinert 2003) and a special issue in the Norwegian Journal of Geology (Solheim 2006).

The Fourth International Symposium on Submarine Mass Movements and their Consequences called for manuscript submissions, addressing the broad issues of submarine mass movements, and meeting the objectives of the project to bring together in a common forum experts from all disciplines pertinent to the topic. This volume is the result: a collection of 62 papers spanning subjects broadly organized under topics of: (1) triggers; mechanics and geotechnical properties; (2) case studies and hazard assessment; (3) margin construction and economic significance; and (4) tsunami genesis from submarine mass movements.

Section I: Submarine Mass Movement Triggers, Mechanics and Geotechnical Properties

A fundamental aspect of submarine mass movement research is understanding trigger mechanisms. This research component, however, is not well developed. In this section, authors explore the role of pore pressure and fluid and gas migration in slope instability. As Masson et al. (this volume) indicate, elevated pore pressures are often essential for mass movement initiation, yet understanding how high pore pressures are generated or how fluid migration affects slope stability is limited. Sediments may be pre-conditioned for failure by the processes that originally deposited them, but the processes and parameters that might control this factor are largely unknown. Continental margin development might also result in focussed fluid flow and elevated pore pressures where sedimentation rates are not particularly high, indicating that margin architecture also plays a significant role in overpressure and the most likely place for occurrence of submarine slope failures (Dugan et al. this volume, Urgeles et al. this volume).

In most historic instances, submarine mass movements were triggered by ground accelerations due to earthquakes. Herein lays a paradox; the majority of submarine mass movements and the largest recognized submarine mass movements occur along passive continental margins, where seismicity is not common. It is a rare instance, therefore, that the actual trigger of a submarine mass movement event has been observed and recorded; the first probably being the 1929 Grand Banks event (Heezen et al. 1952 and 1954). Even during events such as earthquakes, ground accelerations may increase horizontal and vertical loads and cause pore pressure responses in specific geologic horizons. Without instrumented in situ monitoring during such events, the actual physical responses of the geologic column to ground accelerations are not known. The paradox above also illustrates that trigger mechanisms need to be properly balanced against preconditioning factors, especially

sediment characteristics and stress history. For some slopes, the actual trigger mechanism is of little importance; rather, an environment for failure results from a series of preconditioning factors that concur so that the slope may fail under relatively small external loads (triggers).

The second most common trigger mechanism for known historic submarine mass movements has been anthropogenic. For example, coastal construction without due consideration for the local geological and geotechnical conditions, as seen with the Nice airport (Dan et al. 2007) and the port of Skagway, Alaska (Conforth and Lowell 1996). In these instances, increased loads due to construction and ill consideration of pore pressure responses led to down slope sediment movement.

Other submarine mass movement trigger mechanisms have been hypothesised that include elevated pore pressures related to gas accumulation such as might be provided by dissociation of gas hydrate. Gas hydrate dissociation results in loss of solid material, production of free gas, and increased fluid pressures; all which have the effect of reducing sediment strength. Grozic (this volume) explores the relationship between gas hydrate and slope instability in this section through theoretical and laboratory experimentation. A number of other papers explore pore pressure and fluid migration in the roles of mass movement initiation.

A full understanding of slope stability and the kinematics of submarine mass movements requires sediment engineering information. Data need to be at high subsurface resolution in order to identify the presence of geotechnically weak layers upon which a mass movement may initiate. Ideally they would also include large areal coverage to capture lateral variability in sediment properties and changing surface and subsurface morphologies. Detailed digital elevation (bathymetric) maps and correlation with seismic reflection profiles can assist in this requirement. These geotechnical data are technically feasible to obtain, but costly, and if not obtained in situ then questions remain as to their validity. As a result, there are few case studies where sufficient geotechnical data are available; a major shortcoming highlighted in a recent Integrated Ocean Drilling Program offshore geohazard workshop report (Morgan et al. 2009). Section I contains papers using geomechanical testing, physical property measurement and cone penetration testing to assess slope stability and failure kinematics. Typically, we assess failure kinematics based on residual sediment physical properties and failure scar and deposit morphologies. It is rare to know pre-failure conditions and likely impossible to know mechanics of the flow during failure, but numerical modeling (Mazzanti this volume) and flume experiments (Zakeri et al. this volume) for example, can provide insightful information to these important issues.

Section II: Submarine Mass Movement Case Studies and Hazard Assessment

Elevated awareness of the need for better understanding of underwater mass movements is coupled with great advances in underwater mapping technologies over the past two decades. Multibeam sonar, 3D seismic reflection, improved 2D seismic reflection and remote and autonomous underwater vehicle technologies provide

hitherto unparalleled imagery of the geology beneath the oceans. Today, significant portions of continental margins are being mapped with these technologies due to increased offshore exploration and exploitation and government national mapping initiatives (e.g. Pickrill and Kostylev 2007). Increased data coverage has led to an exponential increase in the number of case studies of submarine mass movement deposits; both surficial and buried. Improved resolution has enabled association of mass movement scar and deposit morphologies with kinematics, processes and hazards (e.g. Posamentier 2004; Frey-Martinez et al. 2006). Increased recognition of submarine mass movements also leads to estimation of the relationship between spatial distribution, magnitude and recurrence interval of such events (see for instance Camerlenghi et al. this volume), which is critical for geohazard assessment.

Section 2 consists of case studies of submarine mass movements, demonstrating a variety of failure styles and flow types ranging from slides to debris flows and turbidity currents. These studies also cover a range of tectonic environments, including convergent and passive margins, coastal regions and even lakes and demonstrate risk analysis based on trigger mechanisms (e.g. Nodine et al. this volume).

Section III: Submarine Mass Movements in Margin Construction and Economic Significance

Another outcome of the abundance and resolution of modern marine geoscience data has been identification of mass movement deposits at almost all scales (Camerlenghi et al. this volume). As a result, Section III deals with this realization that mass movements are a natural and geologically common process in slope environments, particularly in coastal regions (e.g. Mosher et al. 2004) and along continental margins (e.g. Mienert et al. 2003). This identification has resulted in cataloging of more and larger submarine mass movement deposits (e.g. Nisbet and Piper 1998; Silva et al. this volume). It is apparent on continental margins, for example, that submarine mass movement deposits form a significant, if not majority proportion of their sedimentary succession (Boyd et al. this volume; Giles et al. this volume). Volumes of single mass movement events can supersede all sources of annual river input to the oceans (e.g. Talling et al. 2007). As a result, they represent a fundamental process in continental margin development, delivering massive amounts of sediment and associated particulate matter (e.g. organics, trace metals) from shallow to deep water. This relatively recent understanding has yet to be adequately accounted for in consideration of sediment and carbon budgets and residence time as well as in sedimentologic and sequence stratigraphic models.

In addition to demonstrating the geologic importance of mass movement deposits in margin construction, Section III demonstrates that these deposits may have an important economic significance. Petroleum geologists are starting to realize that understanding sediment mass movement may be useful in hydrocarbon exploration (Beaubouef and Abreu, this volume; Frey-Martinez this volume e.g. Moscardelli 2006). The capacity of submarine mass movement deposits to modify

the seascape configuration has a profound effect on the distribution of sediments and subsequent stratigraphic relationships. Consequently, submarine mass movements may exert important controls on basin development, reservoir location, geometry, facies distributions, and the possible development of stratigraphic traps. They may also constitute a critical factor in directing fluid flow pathways and in some cases, coarse-grained mass movement deposits may even act as reservoirs (e.g. Beckley et al. 2003; Khafizov and Syngaevsky 2005).

Section IV: Submarine Mass Movements and Tsunamis

Consequences of the 1998 PNG tsunami and the 2004 Sumatran tsunami have been significant improvements in numerical tsunami simulations and recognition that this science requires input from engineering, geoscience, oceanography, geography and mathematics disciplines in order to represent reality. Increased computer processing power and increased sophistication of programming code have led to drastic improvements in numerical simulation of tsunami generation, propagation and inundation in the past few years. Tappin (this volume) emphasises that all forms of submarine mass movements are potentially tsunamigenic, yet there is a paucity of data relating submarine failures to tsunami generation and the physics of the process is still not well understood (Bardet et al. 2003; Lynett this volume).

This final section concerns submarine mass movements and their ability to generate tsunamis, principally through numerical simulation, although analog studies are presented as well (Mohammed and Fritz, this volume). Several papers address the complexities of mass movement materials and processes in tsunami generation. Remaining papers include geologic examples of submarine mass-movements with numerical simulations of tsunamis that may have resulted. In one paper (Poncet et al. this volume), a case is presented for a potential future submarine mass movement and consequent tsunami. In each of these studies, authors address the potential for tsunami generation and assess the hazard to proximal coastlines by estimating wave height, propagation and inundation characteristics. A major limitation to hazard assessment studies is lack of age control and subsequent frequency of occurrence, indicating a need for detailed sedimentological analysis (e.g. Di Roberto et al. this volume).

Looking to the Future

A publication such as this book, stemming from a conference and a call for submission of papers, is somewhat pot-luck. With good fortune, however, a broad cross section of the subject of submarine mass movements and their consequences is represented in this volume. Advancement of the science in this series following the relatively recent inception of the IGCP 511 program has been remarkable. This evolution

is due to the increased area of seafloor mapped at high resolution as well as contributions from industry with quality data sets that are not necessarily accessible to the public or the academic community. In addition, modellers have made great strides in simulating tsunami propagation and inundation.

Despite these great strides, there are yet a number of areas in which advances in the subject area are required. Without a doubt, studies of submarine mass movements drastically lack physical samples, and with samples come geophysical groundtruth, age control and geotechnical information for understanding trigger mechanisms, flow dynamics, recurrence intervals and relationship to Earth's natural climate variations. This shortcoming is because industry generally lacks interest in these deposits and the near-surface section, as it supposedly contains no economic consequence. Despite active academic research interests, scientific drilling is too expensive for individual research institutions to sustain and international scientific drilling programs, such as ODP and IODP have avoided drilling areas with such pronounced geohazards. Even with sample control of mass movement deposits, only so much can be learned; there is a real need to know conditions prior to a submarine mass movement and, if at all possible, conditions during initiation and movement.

The recent increase in exploration and development in deep water has prompted industry interest in sediment mass movement, however. This interest is from both a geohazard perspective and to understand mass movement's role in sediment distribution and its potential for creating hydrocarbon traps and/or reservoirs. Collaboration between industry and academia will be fundamental in the future. In this regard, it is expected that shallow subseafloor and borehole observatories will provide the data to decipher slope conditions at these different stages. For these observatories to succeed, we must be able to identify areas where slope failure is ongoing or might occur in the near future, and we must put to study the relationship between slope deformation, seismic ground shaking, and pore pressure response, amongst other variables. Presently a number of IODP proposals (www.iodp.org) tackle this aspect.

A second research area in need of advancement is quantitative understanding of mass movement initiation and kinematics and energy coupling between movement of the sediment mass and the overlying water column that generates the tsunami. As real case studies of these factors are rare and likely to remain rare, advances in this field will require numerical simulation. Most submarine mass movement-tsunami models assume a relatively simplistic displacement condition to initiate the tsunami wave. With mathematicians turning their attention to this problem, they will likely advance the science before adequate observational groundtruth will be provided.

We expect over the next 5 years that submarine mass movements and consequent tsunami potential will acquire a much higher public profile, as awareness of their risk is revealed. There have also been recent cases whereby identification of submarine mass movements has permitted extension of the definition of the continental boundary under claims with the United Nations Commission for Law of the Sea. Consequently, it is expected that submarine mass movements will become a higher priority research item for many countries, as has already

occurred in the US (e.g. ten Brink 2009). We also expect their relevance to commercial exploration will become better appreciated, and consequently will be incorporated into stratigraphic and sedimentologic models. These models will help refine estimates of global sediment budgets, residence time and associated geochemical variables to help refine global climate change scenarios and possibly lead to discovery of new reserves.

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