Submarine mass movements and their consequences, 2nd international symposium: Summary

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Introduction

Exploitation of offshore resources, development of communication and transport corridors, fishing habitat protection, and the protection of coastal communities, have all contributed to a growing interest in improved understanding of offshore geohazards, in particular seafloor mass movements and their consequences. As the petroleum industry moves into increasingly deeper waters of the world's continental margins, the increased focus on geohazards is also absolutely necessary. We cannot prevent slides from occurring, but we can try our best to understand their triggering mechanisms, their flow patterns, and their impact, in order to reduce the potential risk to installations as well as to third parties. The term tsunami became an integrated part of the public vocabulary after December 26, 2004. Slide-generated tsunamis may in some areas pose significant threats to coastal communities.

The second international symposium on "Submarine Mass Movements and Their Consequences" took place in Oslo, Norway, September 5-7, 2005. Conference themes included:

1. Submarine slope stability studies: present and future.
2. Slope instability as a function of geological setting and sediment properties.
3. Geotechnical criteria for slope instability, from field evidence to models.
4. From static to dynamic behaviour of a sediment mass; Triggering, disintegration, slide dynamics, and run-out.
5. Mechanisms of slide generated tsunamis.
6. Impact of debris flows and turbidity currents on seafloor structures.
7. The risk aspect, including costs and insurance.
8. Submarine archaeology and mass movements.

The conference comprised 83 contributions (49 oral and 34 posters) (Lombaerts et al., 2005). The number of contributions within each theme varies greatly however, and there seems to be a need to encourage more focus on some aspects of the subject for the future.

Different from the First International Conference on Submarine Mass Movements and Their Consequences, in Nice, France, 2003 (Locat and Mienert, 2003), publication of contributions for the present conference was not mandatory, but longer individual papers were allowed. Therefore, the present issue of the Norwegian Journal of Geology comprises 20 of the conference contributions, all representing important aspects of submarine mass movements. Hopefully, the issue will be widely used in the near future, and also serve as a guideline for future studies to advance our field further.

Summary

Several themes are treated through case histories from different continental margins and different depositional and tectonic settings. *Laberg et al.* discuss slides off the margin of northern Norway (north of the Storegga Slide). They investigate and date turbidites, which they interpret as slide generated, and can this way obtain slide frequencies and relate slides to glacial variability. In a totally different setting, *Krastel et al.* report on large slides on the Mauretania margin, off NW Africa. Here high sedimentation rates are caused by upwelling induced biogenic production, and wind-blown dust from Sahara. River-fed depositional systems also played a role in this area during the Holocene, but at the present sea-level highstand, the margin is assumed to be relatively inactive.

Two papers are from the Marquês de Pombal Slide at the Portuguese continental margin. *Vizcaino et al.* provide a thorough overview of the morphology of the slide and sediment stratigraphy in the area. They conclude that the slide most likely was earthquake triggered, but is much too old (3270-1949 years B.P.) to be the source for the 1755 Lisbon tsunami. *Minning et al.*, focus on the physical properties of the sediments from the same area using index property measurements and ring shear tests along with analyses of pore water chemistry. They conclude that the properties of the deposits in the area support a relatively moderate earthquake being the trigger for instability.

Measurement of in-situ properties is important but difficult, and often requires significant logistics, including a drilling vessel. *Stegmann et al.* report on the initial results of a newly designed free-fall cone Penetrometer for use in water depths down to 200m. This device may provide a simpler way of obtaining in-situ geotechnical properties from slide prone areas. The geotechnical causes of slope instability are discussed further by *Huhn et al.* They use a combination of geotechnical experiments on various sediment compositions and numerical modelling to demonstrate the importance of clay mineral content and clay mineralogy for slope instability.

Two contributions are from fjord settings. *Lee et al.* discuss new swath bathymetric data from two fjords in the Gulf of Alaska, where the great Alaska Earthquake and the following tsunamis in 1964 killed 64 people and caused severe damage. The tsunamis most likely resulted from a number of landslides triggered by the earthquake, and a variety of submarine morphological features resulting from these are discussed in the paper. An important issue is that slide scars are not clearly evident and most of the analyses are done on various slide depositional features. In another fjord study, *Levesque et al.* use modelled and measured sedimentation rates in the Saguenay Fjord, Quebec, Canada, to predict the range of possible dates for events of rapid deposition caused by gravity-driven mass movements in the fjord. The results are used to control whether or not the events can be correlated with known earthquakes of the last few centuries, in this seismically active region.

The Storegga Slide has been extensively studied for a number of years, (Solheim et al., 2005), and has become a classic location for studies of submarine slides at high latitude continental margins. Large amounts of data have been acquired from the region, and there is still potential for a deeper understanding of various aspects of this huge slide. *Yang et al.* use geotechnical data of samples from critical stratigraphic levels in the Storegga Slide to explain the slide behaviour. Using a steady state approach, they are able to help explaining the failure of certain units, as well as the long run-out distance which is extreme on such a low slope angle, and also discussed by *Gauer et al* and *De Blasio et al.*

The potential for tsunami generation is one of the major geohazards related to submarine mass movements, and certainly the one which will affect third-party property and individuals the most. In their review paper *Harbitz et al.* discuss aspects of tsunamis generated by submarine slides. The important parameters for determining maximum tsunami surface elevation seem to be the volume, initial acceleration, the maximum velocity and the possible retrogressive behaviour of the slide. The Storegga Slide and tsunami is again a classic event. Slide generated tsunamis typically have very large run-up near the source area, but have much less severe far-field effects than tsunamis generated by earthquakes, such as the December 26, 2004 Indian Ocean event.

Tools for numerical modelling of geological processes, such as mass movements, have improved greatly over the last years, and a set of contributions focus on various aspects of submarine slides using numerical methods. *Niedoroda et al.* used a 2D layer-averaged Bingham fluid numerical model to explore the relative importance of yield stress, kinematic viscosity, bottom slope, and initial failure height on the run-out distance of debris flows. The results show that the most important factor is the Bingham yield stress, whereas the kinematic viscosity of the flow is effective in controlling the speed. Effects of hydroplaning were not considered in this modelling. *De Blasio et al.* look further into the long run-out distances of subaqueous debris flows using both field evidence and results from laboratory experiments in the numerical models. They are able to demonstrate that the dynamical behaviour of the debris flows depends largely on the clay-sand ratio. Clay-rich debris flows, which are typical for glacially influenced areas tend to hydroplane on thin water films, whereas sandy flows lack cohesion, shows a more complicated behaviour, and settle more quickly. The study of *Amiruddin et al.* on the other hand, focuses on sandy debris flows, using both physical and numerical modelling. They show that deceleration occurs, and that a solidification front develops, which clearly separates the fluidized zone of the flow from an accreting sediment layer in which a grain-supported framework is being re-established.

Further work on clay-rich material is reported in the study by *Gauer et al.*, in which results of laboratory experiments are back-calculated. The authors are able to simulate pressure conditions in the ambient water, which facilitate hydroplaning. They also demonstrate velocity differences between the head and the tail of the slide, which can lead to the development of outrunner blocks.

The scale difference between laboratory experiments and real submarine mass movements is a problem. However, outrunner blocks of submarine slides often show a remarkable similarity to experimental data, and may therefore help bridge the gap between the laboratory data and the large real flows. *Engvik et al.* carried out small scale 2D simulations of a theoretical outrunner block. Their results show that the block is able to hydroplane and reach long run-out distances. The thickness of the block is highly correlated with the maximum velocity. Furthermore, the authors are able to model oscillatory movements, which may help explain morphological features observed at the seafloor in front of submarine slides several places.

Gas hydrates have received focus for a number of years. They are considered a potential energy source, a potential environmental problem, and also a geohazard because they can potentially reduce slope stability upon dissociation. Nixon and Grozic developed a model to analyse the impact of hydrate dissociation on submarine slopes as described by the factor of safety. Their model quantifies the increase in pore pressure from dissociation of hydrates and incorporates the resulting decrease in effective stress into the slope stability analyses. The results show that even small amounts of dissociating hydrates can have a significant impact on slope stability, and that slopes located at shallow water are more susceptible to hydrate-induced instability than at deeper waters.

Disregarding the potential for tsunami generation, the ultimate reason why a submarine mass movement can be considered a hazard, is its potential to damage seafloor facilities and infrastructure. Relatively little is done on the impact of mass flows hitting seafloor structures, and this is the focus of the contribution by *Bruschi et al.,* who particularly study the impact on pipelines. In their paper they use field examples from continental margins of the Mediterranean and the Black Sea. After reviewing several scenarios, their main conclusions are that there are at present very large uncertainties, and that much more work is needed in this field. Based on present knowledge, the authors suggest a set of engineering recommendations for the construction of pipelines in slide-prone areas. This is clearly a field with large challenges for future studies.

Another type of impact of mass movements is presented in a paper by *Stanley et al.* on the submergence of the two ancient harbours of Alexandria, Egypt. Their investigations show that failure of the substratum and subsequent mass movement have destroyed constructions in the harbours numerous times since early human occupation in the 1st millennium B.C. These events have happened both in connection with high energy natural events, such as earthquakes, storm surges and tsunamis, but also simply as a results of heavy construction on poor substratum. Construction material and sediments have been transported several 10s of meters offshore. The findings may also help explaining submergence of ancient coastal settings elsewhere.

The final two contributions of this volume deal with risk assessment and financial aspects of submarine mass movements. *Nadim* provides a review of major recent contributions in risk assessment for submarine slides. Risk assessment is not commonly practiced by geo-scientists, and the author presents important aspects of this scientific field, including a very useful glossary of important terms. The paper provides a step-by-step approach for performing a thorough risk assessment of a submarine slide scenario. *Smolka* provides a comprehensive overview of the insurance business' perspective on losses related to natural catastrophes. Loss data on great natural disasters since 1950 show a dramatic increase in catastrophic losses over the last few decades. Although most of this results from natural disasters other than submarine mass movements, problems related to risk management and insurance would be similar as for other natural disasters. The Indian Ocean tsunami of December 26, 2004, is considered a "wake-up call" in this respect, and is used as an example of the problems. Submarine slides may represent a challenge to the insurance industry if high-value oil and gas facilities are affected, or if the slide generates a tsunami large enough to cause damage in coastal areas, and particularly if the event is large enough to have significant far-field effects.

Concluding remarks

The conference also included the kick-off meeting of the new IGCP Project no. 511: "Submarine Mass Movements and Their Consequences", which already had been accepted by UNESCO and IUGS (www.geohazards.no/igcp511). This international project provides the formalised basis for joint efforts in bringing the field of submarine mass movement studies forward. At the time of publication of this volume, the 3rd international conference is being planned for Santorini, Greece in 2007, the themes for which is largely being based on results and identified "knowledge holes" from the first two conferences. Bringing together specialists from different geo-scientific fields, both from academia and industry, is also an important goal. A main aim of the project is to make geologists, geophysicists, geotechnical engineers, physicists, modellers, and others all join forces in understanding as much as possible of the many aspects within the wide theme of submarine mass movements and their consequences.

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