THE NEED FOR UNDERWATER LANDSLIDE HAZARDS PREDICTION

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ABSTRACT

As of early 2000, scientists were unable to assess many underwater landslide hazards, to predict their occurrence following a nearby earthquake, to evaluate their tsunamigenic potential, and to warn coastal communities of imminent danger. Underwater landslides pose a continuous threat to US coastal economic activity, including valuable offshore structures, communication cables, and port facilities. Underwater landslides can generate tsunamis reaching at least 30 m above sea level, surpassing bounds of tsunamis generated by earthquakes. In the 1990s, more than 2400 people perished from landslide tsunamis as villages were swept clean by walls of water moving faster than residents could run, notably during the 1992 Flores Island, Indonesia and 1998 Papua New Guinea events. Local tsunamis also threaten lives and property along most US coastal waters, including Southern California. This fact calls into question the preparedness of US coastal communities for such events and fuels the need for underwater landslide prediction. This report summarizes the motivation for a workshop funded by the US National Science Foundation and reports on the consensus finding of workshop participants.

INTRODUCTION

Underwater landslides or submarine mass movements are generic terms encompassing all sizes and shapes of sediment, rock, and reef failures. Can scientists predict the occurrence, location, and dimensions of underwater landslides for a given continental margin and earthquake trigger? This is the central question that the Workshop on the Prediction of Underwater Landslide Occurrence and Tsunami Hazards off of Southern California attempted to answer from March 10-11, 2000 at the University of Southern California, Los Angeles, California. The basic answer is yes: several methods have already been devised and several were described in presentations at the workshop. However, underwater landslide hazard assessment remains difficult because the accuracy of prediction techniques remains largely unknown, so there are no clear confidence limits. There is also a dearth of sensitivity analyses of existing predictive models, so key physical quantities remain to be identified. The number of case studies applying or comparing predictive models is quite small. The 1998 Papua New Guinea event provides one of the first complete tsunami case studies with modern seismic records, exhaustive onland investigation, several post-event marine surveys, and successful numerical simulations. Predicted probability distributions have rarely been compared with distributions of documented or historic events. A lot of fundamental research remains.

Tsunamis, a Japanese word meaning "harbor waves" or tidal waves, have been traditionally associated with nearshore earthquakes. The largest tsunamis readily propagate across an entire ocean to inflict significant damage and loss of life. From this perspective, either an earthquake generates a tsunami that threatens the entire Pacific Basin, or a credible tsunami threat only exists where the earthquake is felt. Locally, the earthquake is the only tsunami warning needed: the larger the earthquake, the larger the expected tsunami. The Pacific Tsunami Warning Center was created in the mid 1900s following several large transoceanic tsunamis to warn distant places, especially Hawaii, of pending tsunami arrival and potential tsunami amplitude. In contrast, the decade of the 1990s saw numerous modest earthquakes that generated devastating tsunamis without any significant transoceanic tsunamis. The term "local tsunami" was coined to distinguish these potentially surprising events from their transoceanic brethren.

Recent case studies of local tsunamis suggest that underwater landslides can be responsible for most of the devastating impact of local tsunamis. As if to underscore this point, remote tsunami sensors in the open ocean occasionally detect tsunamis following earthquakes where none were expected. Researchers now consider tsunamigenic landslides triggered by the earthquake. Consequently, the term "landslide tsunami" came into use to describe those events where underwater landslides generate the most hazardous local tsunami. The word tsunami can now encompass several tsunami sources generated by different geological events, e.g., earthquakes and landslides. The tsunami amplitude is no longer predictable from earthquake magnitude alone. On the one hand, few underwater landslides are tsunamigenic as they are either too small or too deep to generate an appreciable water wave. On the other hand, some of the largest tsunamis ever produced on earth were landslide tsunamis. Scientific observations and case studies are driving a paradigm shift in our understanding of underwater landslide and tsunami hazards. Effective hazards assessment and local tsunami warning demand that underwater landslide hazards, including tsunamis, be predicted.

WORKSHOP OBJECTIVES

Some invited scientists, both before and after the workshop, perceived that landslide tsunamis constitute a scientific discipline at the juncture of seismology, soil mechanics, marine geology, and fluid dynamics. The juncture is clearly more interdisciplinary and more complex than a simple boundary between two scientific disciplines. However, the perception of a distinct scientific discipline can only be validated by the response of fellow scientists to study natural hazards such as landslides and tsunamis. Is “underwater landslide hazards” an appropriate and desirable label for the collective research effort? A workshop is one mechanism whereby the enthusiasm of the scientific community can be assessed. Therefore, an informal workshop objective was to assemble a group of scientific leaders who could potentially form an established core for the scientific discipline. We canvassed four scientific disciplines to promote the synergies needed to consolidate underwater landslide hazards into one discipline. We eventually hosted 67 registered workshop participants, almost double the number planned for at the outset. The largest contingent of participants were marine geologists. Additional students and staff from the University of Southern California informally attended the workshop. Based on the workshop attendance and interest level of participants, underwater landslide hazards appear to have a promising future. The workshop had the following formal objectives:

- To present the state of the art in science and engineering disciplines related to underwater slope stability and landslide tsunamis;
- To establish the capabilities, accuracy, and sensitivity analyses of existing predictive models in order to hone in on requisite model inputs;
- To gather databases and case studies with which to validate predictive models;
- To focus future research activities on unavailable data and predictive model improvements;
- To write recommendations for research institutions and public agencies, notably the US National Science Foundation;
- To produce a volume summarizing workshop findings for scientific peers.

The workshop considered underwater landslide prediction from seven different perspectives: the probability of failure, the occurrence of failure, the location of failure, the size of failure, the landslide motion following failure, the landslide deformations following failure, and the tsunami features generated by failure. These seven perspectives have different affinities to seismology, soil mechanics, marine geology, and fluid dynamics as well as to existing prediction models. By acknowledging seven perspectives, we hoped to encourage participants to choose a form of underwater landslide prediction most suited to their traditional research.

WORKSHOP ACTIVITIES

The workshop was largely organized through a web site that still lists the participants and the activities: *http:rccg03.usc.edu/la2000/*. We summarize the workshop activities here. The workshop opened with short introductions given by 1) Cliff Astill, US National Science Foundation Program Manager, 2) Eddie Bernard, Director of NOAA Pacific Marine Environmental Laboratory, 3) Ed Clukey, scientist at BP Amoco Inc., and 4) the workshop hosts. The workshop goals were then outlined through case studies presented Tad Murty, Dave Tappin, Eli Silver, Jose Borrero, Costas Synolakis and the author. All but two speakers described various aspects of the 1998 Papua New Guinea event. The main body of the workshop consisted of four technical sessions:

1) Seismic Considerations, chaired by Emile Okal, Northwestern University
2) Sediment/Geotechnical Stability, chaired by James Mitchell, Virginia Tech
3) Mass Failure Field Work, chaired by George Plafker, USGS Menlo Park
4) Mass Failure Computations, chaired by Homa Lee, USGS Menlo Park

At the conclusion of the four technical sessions, Cliff Astill chaired a session devoted to formulating recommendations for the US National Science Foundation. This was accomplished by letting workshop participants join open discussions facilitated by the session chairmen and the workshop hosts. A compilation of these recommendations is featured below.

RESEARCH ISSUES

During the workshop, participants were asked to reflect on the following lists of questions. In many instance, these questions remain research topics that the reader may find worthwhile pursuing. Even questions with apparently simple answers may conceal a wealth of geological or mechanical complexity. We therefore encourage the reader to reflect on each question with an open mind. Answers that address landslide hazards prediction are not always evident from the current state of the art.

Seismic Considerations

How do near-field earthquake ground motions induce the failure of marine sediments? What is the influence of any episodic stress changes on excess water pressure and sediment failure along a margin? Does coseismic displacement during an earthquake correlate with bathymetric highs and lows, and could this help indicate the locations of sediment failure? How do seismic radiation characteristics from mass failure depend on mass failure material and dimensions?

Sediment/Geotechnical Stability

What physical mechanisms are capable of inducing failure of submarine masses? Which sediment parameters affect most failure calculations for various failure mechanisms? Which geotechnical methodologies are available for predicting slope instability? How do local sediment inhomogeneities influence or determine global mass failure characteristics? Given an unstable sediment slope, what mechanisms determine or control the width of failure?

Mass Failure Field Work

What do mass failure morphologies tell us about failure mechanics? Why do so many steep slopes persist adjacent to failed slopes? Is the geological formation of a sediment slope related to the mechanics and probability of submarine mass failure? Can one infer probability distributions for submarine mass failure from observations of failure scars and deposits? What role would borings play in assessing regional failure probabilities?

Mass Failure Computations

How many reasonably complete case studies can one assemble to validate predictive algorithms of submarine mass failure? Under what conditions can a specific failure mechanism be expected to dominate mass failure? What constitutes a reasonably effective stability analysis for a given failure mechanism? Do predicted submarine mass failure probability distributions agree with observed distributions? Which seismic, sedimentary, or geological inputs essentially control or dominate submarine mass failure?

WORKSHOP RECOMMENDATIONS

One of the workshop objectives was to produce a list of recommendations for the US National Science Foundation. These recommendations are intended to be used by the US National Science Foundation, as well as other research institutions. Recommendation have been derived from multiple sources and collated in a manner that gave equal weight to all sources. In addition to the lists of questions mentioned above and distributed on paper forms, we asked workshop participant to provide written answers to the following three questions. What institutions can we establish to promulgate this research community? How can the internet assist us in our goals? Who is the most effective audience for our recommendations? Feedback from all of these queries has been collected here under the rubric of workshop recommendations. Reports from the session chairmen are also summarized here, as are the recommendations formulated at the end of the workshop. These varied sources of recommendations often coincide, which reflects on the level of agreement achieved at the workshop.

Underwater landslide hazards pose research challenges at the intra-agency and inter-agency level to both the US National Science Foundation and the US Office of Naval Research. As an emerging discipline, research on underwater landslide hazards has yet to established its places and roles within institutional structures. Consequently, these recommendations are geared toward facilitating research on underwater landslide hazards. The list of recommendations is provided as a bulleted list.

- Underwater landslide hazards present research opportunities within multiple directorates and divisions of the National Science Foundation. As of now, underwater landslide hazards do not fall neatly into any one directorate. In order to facilitate funding opportunities within the current institutional structure, workshop participants recommended merging support from different divisions to fund underwater landslide hazards research.
- The US government already possesses a wealth of existing marine geology data, much of which can be made or already is publicly available. These data are often an untapped or underused source of information for underwater landslide research and hazard mitigation purposes because of the difficulties involved in finding and requesting the data. In order to facilitate the productive use of this data, workshop participants recommended establishing institutional links to locate and distribute archives from the US Navy, Mineral Management Service, US Geological Survey, etc. to researchers.
- The workshop assembled a new composite of landslide triggering theories. Yet, almost no sites of underwater landslide research either receive or are amenable to a thorough examination of the causes of and potential for underwater landslides. In order to perform a thorough landslide case study and site specific hazard assessment, workshop participants recommended choosing an intensive research site such as Santa Barbara, California. At this site, a thorough suite of tectonic and sedimentary measurements could yield invaluable insight into underwater landslide hazards, improve existing engineering models, validate underwater landslide stability analyses, and enable prediction of future landslide events.
- Underwater landslides form a complex and interdisciplinary research subject that could benefit from further synthesis of disparate modeling efforts. In order to facilitate such syntheses and promote sensitivity analyses of landslide hazards, workshop participants recommended developing a landslide failure community model in order to model 3D failure surface formation, to study early time landslide motion and deformation, and to examine the role of tectonic structures such as faults in failure.
- Landslide tsunami generation remains a poorly understood phenomenon for which there has recently been a proliferation of different numerical models with widely differing assumptions. In order to guarantee and promote tsunami hazard assessment, workshop participants recommended developing a tsunami generation community model including landslide tsunami sources and earthquake tsunami sources.
- Researchers present at the workshop perceived that underwater landslide hazards was a relatively young and rapidly changing scientific discipline. One workshop would not suffice to define the interests and needs of participating researchers. In order to further interdisciplinary collaboration as well as the development of the research community, workshop participants recommended funding another underwater landslide hazards prediction workshop.
- Tsunami warning centers are currently set up to mitigate the impact of distant tsunamis. A felt earthquake was considered sufficient warning for local tsunamis. Devastating landslide tsunamis can appear with little to no felt earthquake, and can possess an amplitude far in excess of any concurrent earthquake tsunami. In order to help save lives endangered by landslide tsunamis, workshop participants recommended developing a prototype local tsunami warning system. Among other goals, such a system would identify and characterize underwater landslides by seismic and acoustic techniques.
- Post-event tsunami surveys during the 1990s have revealed a wealth of information regarding landslide tsunami hazards. Nevertheless, significant events are sufficiently rare that there remains much to confirm and even more to learn. In order to further understand the onland impact of landslide tsunamis, workshop participants recommended continuing support of International Tsunami Survey Teams.
- Marine surveys are proving valuable tools for understanding and modeling landslide tsunami generation. However, only a handful of such surveys have been carried out and the inherent complexity of geological systems will require many more before patterns emerge. In order to further understand the offshore generation of landslide tsunamis, workshop participants recommended continuing support for marine surveys of tsunami source regions.

- The private sector has significant financial concerns exposed to underwater landslide hazards. In order to further prediction of underwater landslide hazards, workshop participants recommended seeking private research support, perhaps from oil and gas producers, insurance companies, or port facilities.
- There are a significant differences between the needs of researchers and the needs of disaster managers. In order to promote underwater landslide hazards mitigation, workshop participants recommended producing consumable tsunami hazard products such as underwater landslide hazards maps, probability distributions of landslide and tsunami events, observed landslide and tsunami recurrence rates, underwater landslide hazards risk analyses, hazard mitigation and preparation measures, cost/benefit analyses, and port survivability studies.
- Researchers need regular contact to keep their research up to date and to expand interest in their field. In order to promote common research interests and share the latest research results, workshop participants recommended organizing Special Sessions at AGU Meetings and other scientific events.
- Researchers need printed venues in which to publish their latest work. For a relatively new research discipline, this can be especially difficult. In order to promote common research interests and share the latest research results, workshop participants also recommended organizing special issues of recognized journals.
- Hazard mitigation in general often involves public education. In the case of tsunami hazards, public education has proven particularly effective at saving lives. In order to promote tsunami hazard mitigation, workshop participants recommended increasing public awareness of tsunami hazards through press releases, news conferences, television programs, web sites, tsunami animations, etc.

CONCLUSIONS

The workshop considered the state of the art in seismology, soil mechanics, marine geology, and tsunami generation as a starting point in underwater landslide hazards research. During the workshop, it became clear that new synergies are indeed providing opportunities to predict underwater landslide hazards. Landslide tsunamis motivate the urgent need for prediction, although other underwater landslide hazards are also of serious concern. Given the sparse temporal and spatial distribution of large underwater landslides, prediction is a crucial aspect of hazard assessment and hazard mitigation. On the one hand, relatively new marine geology tools enable a broader assessment of ocean floor stability, while on the other hand engineering models merge previously distinct aspects of landslide failure into predictive models. These interdependent opportunities feed the growth of a what some workshop participants termed a scientific discipline unto itself. The objectives of this discipline will include the prediction of the probabilities, locations, dimensions, motions, deformations, and hazards of prospective underwater landslides.

Landslide tsunamis pose the greatest local tsunami threat according to a consensus opinion of the 67 scientists attending the workshop. Tsunamis are one of the most important natural hazards facing the five Pacific US states, occasionally inflicting more damage and casualties than large earthquakes -- viz., the 1964 Alaskan earthquake. Local tsunamis have reached 15 m above sea level during the 1998 Papua New Guinea tsunami and 26 m above sea level during the 1992 Flores Island, Indonesia tsunami, both due to nearby underwater landslides. More than 2400 people perished from these tsunamis as villages were swept by churning walls of water moving faster than residents could run. The 1998 Papua New Guinea event has proven to be and will likely continue to be a valuable case study with which to validate models of underwater landslide hazards. To be sure, more case studies are needed, some of which should be based on the data and expertise acquired by oil and gas producers as well as the US federal government. Workshop participants have chosen the Santa Barbara, California continental slope as an ideal case study that can involve most interested scientists, agencies and institutions.

An interdisciplinary approach to underwater landslide hazards assessment will eventually yield probabilistic and deterministic predictions of submarine mass failure size and location. These predictions will enhance both underwater landslide hazards assessment and local tsunami warning capabilities. The capabilities and sensitivities of existing predictive models have established certain critical parameters that may control some underwater landslide hazards. Future research activities should focus both on reducing uncertainty and enhancing predictive model capabilities. Workshop recommendations have been written for public and private agencies and institutions. We are confident that the workshop has advanced our ability to assess underwater landslide hazards. We perceive our future goals as a continuation of the workshop goals: to predict underwater landslides, to assess underwater landslide hazards, to evaluate their tsunamigenic potential, and to warn coastal communities and other entities of imminent danger.

ACKNOWLEDGEMENTS

The workshop was supported by the US National Science Foundation, through a grant made to Jean-Pierre Bardet and Costas Synolakis at the University of Southern California. The author wrote the research proposal and organized the workshop proper. Support for writing this paper was also provided by Applied Fluids Engineering, Inc.