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Landslide Tsunamis: Recent Findings and Research Directions

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Abstract—Underwater landslides can trigger local tsunamis with high runup, endangering human life and devastating coastal cities, offshore structures, communication cables, and port facilities. Unfortunately, hazards from underwater landslides are not well understood and the extents of their potential damage remain difficult to ascertain at present. There is immediate need for multidisciplinary research to improve our understanding and plan countermeasures for mitigating their hazards. Conceived in the wake of the Papua New Guinea earthquake landslide and tsunami of 1998, this volume summarizes the state-of-the-art knowledge on underwater landslides and their potential to generate tsunamis from the multidisciplinary perspectives of observational and engineering seismology, geotechnical engineering, marine geology, and hydrodynamics. These various fields of engineering and science offer new synergetic opportunities to examine landslide tsunamis. This paper makes recommendations on future research directions, and will hopefully advance scientists' and engineers' understanding of these natural hazards and assist planners in mitigating their risks.

Key words: Landslides, tsunamis, engineering seismology, marine geology, geotechnical engineering.

1. Background

Tsunamis – a Japanese word translating into "harbor waves" – have inflicted significant damage and casualties along coastlines, even after propagating vast distances across open oceans. In the last sixty years, tsunamis generated by distant earthquakes have killed more people in the United States than earthquakes within the United States. Between 1942 and 1995, tsunamis were responsible for 351 dead, whereas earthquake and tsunamis together caused a total of 627 casualties (Stover and Coffman, 1993; Lander and Lockridge, 1989). In the aftermath of the 1946 Aleutian tsunami, the Pacific Tsunami Warning Center was established with the goal of protecting coastlines from distant (far field) imminent tsunamis. Hazards from

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transoceanic tsunamis are now mitigated by the issuance of early warnings to evacuate coastal areas at risk; these early warnings are based on seismic and tide gage data telemetered to the warning stations, a handful of deep ocean recorders, and simulated scenarios (*e.g.*, PARARAS-CARAYANNIS, 1986). Unfortunately the existing warning systems are not in fact helpful for tsunamis triggered close to populated coastlines, as the propagation times are short from tsunami generation to runup.

Since the 1960s, and particularly after the 1964 Alaskan tsunami, considerable effort has been devoted to understanding tsunamis from generation to coastal inundation (*e.g.*, BEN-MENAHEM and ROSENMAN, 1972; WARD, 1980; OKAL, 1988; SATAKE and KANAMORI, 1991). By 1990, the problems of transoceanic propagation of tsunamis and harbor resonance effects were believed well understood. In the 1990s, computational advances led to better modeling of tectonic source mechanisms and new generations of coastal inundation models (*e.g.*, IMAMURA *et al.*, 1995; TITOV and SYNOLAKIS, 1998). These advances were also made possible due to large-scale laboratory experiments, analytical results, and especially post-tsunami field surveys (*e.g.*, YEH *et al.*, 1993; SATAKE *et al.*, 1993; SYNOLAKIS *et al.*, 1994; TSUJI *et al.*, 1995; KAWATA *et al.*, 1999). Indeed, post-tsunami reconnaissance of coastal inundation after the ten large tsunamis of the 1990s have provided hydrodynamic modelers with opportunities to understand the natural processes at work and to validate computational models. Despite such progress in modeling, some tsunamis are still defying all analyses – underwater landslide tsunamis. Landslide tsunamis present a particularly vexing problem, not only because they can be triggered sometimes unexpectedly after a strong earthquake, but also because the propagation times to the target coastlines can be as short as one minute, as in 1994 at Skagway, Alaska (KULIKOV *et al.*, 1996; SYNOLAKIS *et al.*, 2000).

The potential that major tsunamis could be generated by massive submarine mass failure (a broad geological term that includes underwater slides and slumps, SCHWAB *et al.*, 1993; PRIOR and COLEMAN, 1979) was recognized a century ago by MILNE (1898), MONTESSUS DE BALLORE (1907), and later by GUTENBERG (1939) and AMBRASEYS (1960). In more recent years, many studies have supported the scenario that a major tsunami could be generated by a large submarine mass failure, itself induced or triggered by a large earthquake in a coastal area. In addition to the well documented cases of Grand Banks in 1929 (HASEGAWA and KANAMORI, 1987), Kalapana, Hawaii in 1975 (EISSLER and KANAMORI, 1987), and the ongoing speculation about the great 1946 Aleutian tsunami (KANAMORI, 1985; OKAL, 1992), careful analyses of runup patterns along shorelines often reveal a peaked distribution, with very intense and localized maxima, generally attributed to a local submarine mass failure, against the background of a more regular wave amplitude reflecting the coseismic dislocation. Such observations were reported for localities in Prince William Sound during the great 1964 Alaska earthquake (PLAFKER *et al.*, 1969).

Surprisingly, the significance of these early reports of landslide tsunamis has not been fully appreciated in coastal planning and management. As urban and industrial development has intensified along the world's coastlines, people and facilities have become exposed to greater risks from underwater landslide tsunamis. The U.S. Geological Survey has devoted substantial effort to identify hazards from aerial and underwater landslides and to infer probable areas of historic landslides. Yet considerable portions of the U.S. coastlines remain unmapped with high-resolution imaging techniques, leading to the underappreciation and underestimation of offshore landslide hazards.

Recently, a few well-documented events have helped focus the attention on landslide tsunamis. During the 1992 Flores Island, Indonesia earthquake (YEH *et al.*, 1993), at the village of Riangkroko, far east along the coast from the most affected region, runup was measured at 26 m, the highest anywhere on Flores Island. The waves that utterly destroyed the village of Riangroko and claimed 122 lives probably originated from a nearby underwater landslide. Some researchers (*e.g.*, IMAMURA *et al.*, 1995) hypothesized that the mechanism was probably similar to those observed during the 1964 Good Friday earthquake in Alaska (*e.g.*, LANDER and LOCKRIDGE, 1989; NATIONAL ACADEMY OF ENGINEERING, 1973; PLAFKER *et al.*, 1969). The 1994 Mindoro, Philippines strike-slip earthquake triggered a tsunami that moved a 6,000 ton barge, 1.5 km inland, most probably from a submarine landslide (IMAMURA *et al.*, 1995). These events were not then recognized as the messengers they were, until the 1998 Papua New Guinea (PNG) catastrophe. Shortly after a magnitude 7 earthquake, 10-m waves swept over a sand spit, completely destroying three villages and claiming more than 2200 lives. The field observations – exceedingly large wave amplitude, delayed time of wave arrival, and limited extent of coastal devastation – all pointed to a landslide tsunami. Shortly after the PNG tsunami, the Japan Marine Science and Technology Center and the National Science Foundation funded marine surveys to investigate the offshore geology and its relation to the tsunami source. Since then, the source mechanism of the PNG tsunami has been extensively investigated (*e.g.*, GEIST, 2000; HEINRICH *et al.*, 2000; IMAMURA and HASHI, 2003; KAWATA *et al.*, 1999; KIKUCHI *et al.*, 1998; SATAKE and TANIOKA, 2002; SWEET *et al.*, 1999; SYNOLAKIS *et al.*, 2002; TANIOKA and RUFF, 1998; TANIOKA, 1999; TAPPIN *et al.*, 1999, 2001). The source mechanisms of many other tsunamis have also been retrospectively evaluated to investigate whether or not landslide tsunamis could be possible explanations for unexplained wave measurements and observations. Examples of such investigations include those during the 1992 Flores, Indonesia event (IMAMURA *et al.*, 1995), and during the recent Kocaeli, Turkey earthquake (YALÇINER *et al.*, 1999), and the 1999 Pentecost Island, Vanuatu tsunami (CAMINADE *et al.*, 2001). Landslides can also explain minor tsunamis during strike-slip earthquakes on nearby on-land faults, for example, following the 1989 Loma Prieta earthquake (MA *et al.*, 1991). It is clear that landslide tsunamis could be delayed for a few minutes to a few tens of minutes after the earthquake main events due to the delayed failure of metastable sediment, or to a mild secondary trigger (aftershock) tipping a precarious balance (BJERRUM, 1971; MURTY, 1979; TURNER and SCHUSTER, 1996).

Characteristics of tsunamis generated by coseismic dislocations and mass failures (*e.g.*, landslides) can be compared in general terms by considering the vertical deformation of the seafloor associated with each type of event (SYNOLAKIS *et al.*, 2002). In the case of underwater mass failure, the vertical deformation of the seafloor is controlled by a combination of the dimension of the sliding mass and the motion of its center of mass, both easily reaching hundreds of meters. In the case of coseismic dislocations, a practical upper bound on seafloor deformation during even the largest earthquakes is usually several meters (PLAFKER, 1965; KANAMORI, 1970), exceptionally reaching 20–30 m (PLAFKER and SAVAGE, 1970; KANAMORI and CIPAR, 1974). On the other hand, the linear dimension of an underwater landslide will rarely exceed 100 km (although the resulting turbidity current could extend over a greater distance, *e.g.*, PIPER and AKSU, 1987), while catastrophic earthquakes can rupture faults along close to 1000 km (KANAMORI, 1970). These order-of-magnitude arguments then predict that seafloor dislocations will result in tsunamis featuring greater wavelength and longer periods, and in turn, in a potential for transoceanic devastation, whereas those caused by mass failures are more geographically contained, even though they may give rise to higher amplitudes in the near field (PLAFKER *et al.*, 1969; SCHWAB *et al.*, 1993).

Current research has demonstrated that modeling of landslide tsunami hazards requires information and data from seismology, marine geology, geotechnical engineering and hydrodynamics. The outcomes of hydrodynamic simulations were found to depend largely on the assumptions made on the geological and geotechnical processes governing mass failures. These discoveries raised fundamental issues in the modeling of tsunamis, especially about the prediction of future mass failure events.

2. *Objective of Present Volume*

In the wake of the devastating 1998 Papua New Guinea tsunami, the editors of the present monograph concerted to organize a comprehensive volume hosted by the journal *Pure and Applied Geophysics*. Some of the papers in this volume originated from a workshop on landslide tsunamis, which was sponsored by the National Science Foundation at the University of Southern California on March 10–11, 2000. The main objective of the workshop was the prediction of the occurrence, location, and dimensions of underwater landslides as well as their tsunamigenic capabilities for continental margins located in earthquake areas. Other specific objectives were (1) to summarize the state-of-the-art in various disciplines dealing with underwater landslides and tsunamis; (2) to document existing case studies on landslide tsunamis; (3) to review the capabilities of existing models; and (4) to provide recommendations to the U.S. National Science Foundation for future research leading eventually to a better assessment of landslide tsunami hazards. The workshop, which was attended by 67 participants, presented interdisciplinary perspectives of engineering seismology, geotechnical engineering, field investigation in marine geology, and hydrodynamic modeling. Underwater landslides were examined from different perspectives, including physical mechanisms, location, size, motion, and implications on wave generation.

3. Main Findings

The 19 papers of this volume document the findings on landslide tsunamis in the wake of the devastating 1998 Papua New Guinea tsunami. The papers were edited to remove technical jargon and to facilitate exchanges of information across the multidisciplinary fields that study landslide tsunamis. The papers, which complement each other and present multidimensional facets of the ongoing research on landslide tsunamis, have been regrouped into the following five categories.

3.1 Modeling Earthquake Ground Motions and Source Characteristics

The characterization of earthquake ground motion is critical to predicting landslide-induced tsunamis. Earthquake shakings are regarded as one of the main triggering mechanisms of mass failures along the U.S. West Coast. Strong ground motions may destabilize slopes by overtopping static gravity forces with transient inertial forces, building up pore water pressure within slope materials, and therefore weakening their shear resistance.

SOMERVILLE and GRAVES (2003) review the current concepts in engineering seismology and the recent advances in modeling earthquake strong ground motions. They provide a useful list of state-of-the-art references on the modeling of strong ground motion. They document that earthquake ground motion can be modeled even near fault ruptures and within basins, in areas where submarine landslides are likely to occur. They report on numerical ground motion models based on seismological theory, which include the effects of near-fault rupture directivity effects, crustal waveguide effects, and basin response effects. These models have been validated against recorded ground motions, and used to estimate the ground motions of past earthquakes and predict the ground motions of future scenario earthquakes.

Engineering seismology is essential in modeling landslide tsunamis as it helps to define the seismic conditions (*i.e.*, intensity and duration of earthquake ground motions) that may induce the failure of marine sediments in study areas. Most engineering seismology studies have mainly been focused on the modeling of transient ground motions relevant to structural responses on land; unfortunately, to our knowledge, they have not been calibrated as extensively from strong motion recording data on the seafloor and at the probable depth of tsunami sources. In view of the recent progress in force-balanced strong motion instrumentation, there is hope that new strong motion instruments will be deployed and data collected on seafloors of coastal areas and will in the future yield a better definition of seafloor transient motion.

The modeling of landslide tsunamis requires, in addition to a better characterization of earthquake ground motions, an understanding of earthquake source mechanisms and of the waves originating from mass failures.

HURUKAWA *et al.*, (2003) present a detailed investigation of the three-dimensional distribution of the aftershocks of the 1998 Papua New Guinea earthquake, with the help of data recorded by a portable network of stations deployed in the epicentral area for a period of two months following the mainshock. They conclude that the shallow-dipping plane is indeed the fault plane, thus supporting the interpretation of the event as underthrusting of the Australian plate by the Bismarck Sea platelet, and constraining the geometry of the field of seafloor deformation in any dislocative model of the source of the tsunami.

OKAL (2003a) addresses the question of the hydroacoustic signature of landslides by examining *T*-phase wavetrains recorded across the Pacific Ocean following the 1998 Papua New Guinea earthquake. He identifies one such wavetrain generated 13 minutes after the mainshock and featuring an enhanced duration, as compared to events of similar seismic magnitudes; the signal is also richer at high frequencies (7 Hz) than typical of small aftershocks. These characteristics, interpreted as expressing a different kind of hydroacoustic source, are generally compatible with a sliding or slumping process. This provides a scenario for the generation of the local tsunami by an underwater mass movement, complete with a precise timing, the latter resolving the reported time discrepancy between the mainshock and the onslaught of the tsunami on the local beach. If confirmed in future studies of underwater events, spectral properties of hydroacoustic signals could open – at least in principle – the possibility of identifying major, possibly tsunamigenic, landslides in the hydroacoustic record, along the lines suggested by CAPLAN-AUERBACH *et al.* (2001) for underwater volcanic events in Hawaii.

3.2 Modeling Landslides in Geotechnical Engineering

Geotechnical engineering is a discipline that complements seismology as it explains some of the physical mechanisms causing the failure of submarine masses. Geotechnical engineering has had some prior experience with the relationship between landslide and tsunami (*e.g.*, SEED *et al.*, 1988). This volume contains two papers in geotechnical engineering useful to ascertain the parameters controlling sediment failure, and to identify the geotechnical methodologies available for predicting the instability of inclined seafloors.

WRIGHT and RATHJE (2003) review earthquake-related triggering mechanisms for submarine and shoreline slope failures. Triggering mechanisms range from direct effects, such as inertial forces from earthquake shaking, to indirect effects, such as rapid drawdown that occurs when an earthquake-generated tsunami first approaches a shoreline. Soil shear strength is an important factor in earthquake-related slope failures. Earthquakes change the shear strength of the soil by inducing excess pore water pressures. These excess pore water pressures change with time after the earthquake, resulting in changes in shear strength and slope stability with time. WRIGHT and RATHJE (2003) show that delayed slope failures after an earthquake can occur as a result of changes in earthquake-induced excess pore water pressures and shear strength with time.

FINN (2002) emphasizes the effects of liquefaction on the stability of sediment deposits. With few exceptions, large landslides have occurred in material susceptible to liquefaction, particularly during earthquakes. FINN (2003) examines the case history of the Seward landslide during the 1964 Alaska earthquake, and reviews the analysis methods used for determining the triggering of liquefaction, and the residual strength of liquefied materials. He also reviews numerical methods available for estimating the displacement of liquefied soils, with specific applications to liquefaction-induced ground deformation in gently sloping grounds and earth dams.

3.3 Post-tsunami Field Surveys

Post-tsunamis field surveys are critical to the studies of underwater landslide tsunamis, as they document what actually occurred in the field. Based on the lessons learned from field observations of past landslides, one may hope to infer the physical and mechanical conditions at the onset of failure, and to distinguish the morphologies of stable and unstable seafloors. Marine geological observations on sediment slopes, including boring, failure scars and slumps, can assist in assessing the probability of submarine mass failure. This volume contains five papers related to the field surveys of the 1998 Papua New Guinea (PNG) tsunami.

DAVIES *et al.* (2003) reconstruct the sequence of events during the tsunami attack, based on a comprehensive program of interviews of survivors and field mapping, started in the immediate aftermath of the disaster, and continuing to this date. Their most important results concern the extent of the zone of extreme devastation along the coast (12 km), the quantification of the runup, their interpretation of the largest amplitudes as the result of interaction with the shore, and the constraints put on the timing of the arrival of the wave at the various locations along the shoreline. The compilation of additional information on subjects as diverse as the possible escape of gases before and during the earthquake and tsunami, the nature of the vegetation species most resistant to uprooting by the wave, and the sighting of unusual lights immediately following the main earthquake, raises challenging problems of interpretation, but may eventually shed light on the processes accompanying the destabilization of the ocean floor during a major earthquake and/or landslide.

MATSUMOTO and TAPPIN (2003) report the result of three cruises carried out in the immediate aftermath of the PNG disaster, and aimed at documenting underwater topographic features which may have played a role in the generation of the tsunami. The first one, using *R/V Kairei*, performed a detailed bathymetric survey and identified the major faults in the area, which were found to be too old to have been involved in the 1998 earthquake. The second and third surveys used the Remotely Operated Vehicle *Dolphin-3K* and the submersible *Shinkai 2000* to conduct visual exploration of the ocean floor. These surveys identified a number of slumps, including a very fresh one in the amphitheater, which can be interpreted as the source of the tsunami. Piston core analyses suggest that, at that location, the slumping involved the motion of a cohesive block.

SWEET and SILVER (2003) report the result of their high-resolution two-dimensional seismic reflection survey along the northern continental margin of Papua New Guinea, in the source region of the 1998 tsunami. Their two-dimensional seismic reflection profiles image several faults, bottom simulating reflectors indicative of gas hydrates, and importantly a large rotational slump. One of their profiles displays the internal structure of a slump within a large amphitheater previously recognized in the bathymetry. They conclude that the central part of the slump is a coherent block with parallel reflections that are tilted back toward the head of the slump, indicating rotation. They also infer a basal failure plane at a maximum depth of 760 m below the seafloor, which outcrops at a steep escarpment, about 100 meters high, located 4.5 km north of the head scarp. The cross-sectional area of the displaced mass is 2.3 km^2. From the bathymetry, the width is approximately 2.5–3 km, yielding a total volume of 3.8–4.6 km^3. Based on these interpretations, they reconstitute the undeformed position of the slump, and found that the center of mass dropped 380 m vertically, moved 840 m horizontally and slipped 980 m along the slide plane.

GELFENBAUN and JAFFE (2003) describe the results of a survey of erosion and sedimentation during the 1998 Papua New Guinea tsunami. Based on four transects spread over a 20-km section of coastline, they document erosion of the beach and berm up to 150 m inland, followed by deposition up to 750 m inland, the average thickness of the deposit being 8 cm, with a maximum of 26 cm. They estimate that as much as 2/3 of the deposits were carried from offshore, rather than moved from the beach and berm, a significantly higher fraction than observed for other recent tsunamis (SHI *et al.* 1995; SATO *et al.* 1995), suggestive of a different mode of interaction between the wave and the deep ocean floor.

Finally, DENGLER and PREUSS (2003) report on the social aspects of the 1998 Papua New Guinea disaster, in the general context of the mitigation of tsunami hazard along comparable segments of coastlines. The compilation of the destruction and loss of life in the various villages along the coast is an important step in the reconstruction of the physical agents and mechanisms directly responsible for the destruction. The authors conclude by listing a number of lessons learnt in Papua New Guinea for tsunami mitigation. In particular, and beyond the obvious danger of the narrow sand spits and the value of education and preparedness, they point out the mixed effect of vegetation whose debris can become battering rams when floated by successive waves.

3.4 Studies on Past, Present, and Future Potential Tsunamis

Besides field surveys, there is a great need for studies to reinvestigate past tsunamis (*e.g.*, TANIOKA and SATAKE, 1996; GUIBOURG *et al.* 1997). There is also a need for marine geology studies and pre-event field surveys (LEGG and KAMERLING, 2003) to detect seafloor morphology that may generate tsunamis; a need for computer simulation to understand the formation of seafloor deposits and time-dependent stability (SYVITSKI and HUTTON, 2003); and a need to understand parameters controlling the generation and propagation of the resulting waves (IMAMURA and HASHI, 2003; SATAKE and TANIOKA, 2003) and in particular the influence of frequency dispersion on near-field propagation (LYNETT *et al.* 2003).

LEGG and KAMERLING (2003) remark that there are major potential submarine slides in the California Continental Borderland, which are capable of generating local tsunamis, invoking large seafloor relief, shallow metamorphic basement, and seismic activity. They report on the Catalina Schist basement complex of the Borderland, which contains clear evidence of a history of deep subduction underthrusting and subsequent tectonic exhumation, and displays steep escarpments which provide slip surfaces with free faces susceptible to failure. They describe two slope failure examples west of San Diego, including large block-glides and progressive rotational slumps along the steep northeast-facing Thirtymile Bank escarpment and along the southwest flank of Fortymile Bank.

SYVITSKI and HUTTON (2003) recommend the use of computer simulation to model the fill of sedimentary basins, in order to examine the location and attributes of sediment failure on continental margins and to infer the runout of their associated sediment gravity flows. Based on numerical experiments, they show how the evolving boundary conditions of sea-level fluctuations, floods, storms, and tectonics control the rate and size of slope instabilities. They characterize the failure potential of finite-slope of marine deposits using a factor-of-safety analysis and tracking deposit properties (*i.e.*, pore pressures, grain size, bulk density, and porosity). They are able to determine whether the failed material will travel down slope as turbidity current or a debris flow. Their computational methodology is illustrated with examples explaining the presence of debris flow deposits in fjords dominated by turbidity current deposition, and the seaward progression of glaciated margins. SYVITSKI and HUTTON (2003) synthesize many of the physical processes that shape seafloor morphology, and simulate the formation of observed features of diverse margin evolutions that took place over thousands of years.

IMAMURA and HASHI (2003) present a number of hydrodynamic simulations of the generation and propagation of the 1998 Papua New Guinea tsunami in the near field, based on precise bathymetry even in the shallowest waters. They conclude that the three key observations revealed by the field surveys, *i.e.*, the maximum runup, its distribution along the coast, and the timing of the waves, require supplementing the earthquake with a small, concentrated landslide of 4 to 8 km^3, delayed on the order of 10 minutes after the mainshock. They also conclude that the tsunami generated by the seismic dislocation was locally too small to be observed or reported by the population.

SATAKE and TANIOKA (2003) use hydrodynamic simulations both in the near and far fields to examine several models of tsunami generation following the 1998 Papua New Guinea earthquake. In particular, they model the effects of a splay fault, branching off the fault ruptured during the mainshock, in a geometry reminiscent of FUKAO's (1979) model of the 1975 tsunami earthquake in the Kurile Islands. SATAKE and TANIOKA (2003) conclude that far-field observations cannot resolve a landslide or a splay fault, and can generally be modeled using the earthquake as the source of the tsunami. On the other hand, the near-field runup requires an additional source, which they suggest could be either a landslide or a splay fault. They also estimate the volume of displaced water and its potential energy from the order of magnitude of tsunami amplitudes in the far and near fields, respectively.

LYNETT *et al.*, (2003) examine the influence of both initial conditions and analytical approximations on the results of hydrodynamic simulations. They examine critically the database on the runup and inundation surveyed in Papua New Guinea, and discuss the correct interpretation of vertical measurements as depth flow, rather than runup, under the particular situation of a sand spit. They carry out numerical simulations using both the Non-Linear Shallow Water (NSLW) approximation, and the Boussinesq equations, which assume a less stringent condition on the ratio of water depth to wavelength, and take into account the frequency dispersion of the wave. They conclude that while the amplitude of the free surface disturbance is largely insensitive to the choice of approximation, both its timing and the resulting wave shapes are strongly affected by dispersion. They similarly test several sets of initial conditions, corresponding to different shapes of initial deformation of the sea surface, and conclude to the general robustness of free surface elevation in front of the beach (and eventually of runup).

3.5 Mechanism of Tsunami Generation by Landslides

All submarine landslides do not have identical capabilities of generating tsunamis (WATTS, 2000; WARD, 2001). A critical aspect of landslide tsunami research is to define the circumstances under which landslides may efficiently generate tsunamis. This volume contains four papers that deal with the efficiency of landslides to generate tsunamis.

MURTY (2003) invokes basic physics to scrutinize the validity of hydrodynamic simulations as applied to landslide tsunamis. He reminds us that tsunami generation from submarine landslides depends mainly on the volume of the slide material and to a lesser degree on other factors including: angle of the slide, water depth, density and speed of the slide material, duration of the slide, etc. Based on a data set of volume V of slide and maximum amplitude H of the resulting tsunami waves, he derives a simple linear regression relationship between H and V. He repeats the exercise with another data set from published literature but using numerical simulation results, instead of observations. Surprisingly, he finds a rather poor agreement between the results of numerical simulations and observations. He concludes that the origins of this discrepancy are not clear, but are large enough to justify some cautions when applying hydrodynamic simulation codes to landslide tsunamis.

RUFF (2003) examines energy balances for tsunamis originating from earthquakes and landslides. He notes that submarine landslides have generated tsunami hazards to near-source coasts, and that ongoing exploration of the oceans has revealed large paleo-landslides in many places. He compares the relative contribution of faulting and landslides to tsunami generation. RUFF (2003) points out that only a small fraction of earthquake energy (less than 1%) is converted into tsunami energy, which is anyway enough energy to generate large tsunamis. For simulating landslide tsunamis, he uses a physical model based on a 2-D block sliding on a constant-angle slope, and solves the problem of wave transients using a Green's function approach. His main finding is that landslides generate the largest waves when the ratio of initial water depth (H_0) above the block to downslope vertical drop ($W \sin \theta$) of the block is less than 1. His model predicts that the conversion factor of gravitational energy into tsunami energy varies from 0% (slow-velocity slide in deep water) to about 50% (fast-velocity slide in shallow water). Great earthquakes produce wave amplitudes of a few meters at a wavelength fixed by the fault width in the range of 100 km. Submarine landslides produce wave heights related to block height b, and have wavelengths that scale with block width. In most case scenarios, landslide tsunamis have small wave amplitudes. However, for small friction and $H_0/W \sin \theta < 1$, wave heights can reach b and $b/4$ in the downslope and upslope directions, respectively. For submarine slides, b can have values ranging from a few meters to several kilometers. RUFF (2003) concludes that under some circumstances submarine landslides can generate large tsunamis.

OKAL and SYNOLAKIS (2003) propose a simpler physical model than RUFF (2003). They evaluate and compare the orders of magnitude of the energy generated into a tsunami wave using two different source mechanisms: (1) seismic dislocations and (2) underwater slumps. Based on simple physical models, they conclude that these two sources can generate tsunamis of comparable energy. They remark that the slumping source is dipolar in nature, and has low frequency deficiency in the far field. Their conclusions corroborate the interpretation that the 1998 Papua New Guinea tsunami was indeed generated by an underwater slump, as per SYNOLAKIS *et al.* (2003).

Finally, OKAL (2003b) explores theoretically the differences in far-field tsunami excitation by dislocation and landslide sources, using the normal mode formalism introduced by WARD (1980). He shows that the spectrum of landslide-generated tsunamis is expected to be shifted to relatively high frequencies, where dispersion effects act to further reduce significantly far-field amplitudes. He proposes order-of-magnitude estimates scaling the energy channeled into the tsunami by dislocations and landslides of variable sizes, and suggests that far-field directivity can be a robust discriminant of the nature of the tsunami source, since highly directive radiation patterns cannot be generated by landslides with physically acceptable values of the sliding velocity.

4. Main Observations and Recommendations

Four main consensual points emerge from the papers in this volume:

- Underwater landslide tsunamis are definite hazards to the world coastlines, especially in areas vulnerable to strong groundshaking such as the Pacific Coast of the United States.
- The observations and modeling made in the aftermath of the Papua New Guinea event demonstrate that no comprehensive model covers all aspects of landslide-induced tsunamis from source mechanism to coastal inundation.
- Research must be carried out urgently so as to reduce the risks on the population and industrial developments along the West Coast of the United States.
- Landslide tsunamis require multidisciplinary studies that build upon experiences in engineering seismology, geotechnical engineering, marine geology, modeling of sediment deposition and runoff, and hydrodynamics.

The following recommendations are made to the U.S. National Science Foundation to improve our understanding and predictive capabilities of landslide tsunamis, and to decrease the hazards they pose to population. These recommendations are listed below without having been prioritized.

- Data remain a critical element in evaluating the risks associated with landslide tsunamis. A large amount of data presently collected is relevant to research on underwater landslide hazards. Unfortunately those data are handled by separate and uncoordinated entities, *e.g.*, Navy, Mineral Management Service, US Geological Survey. Coordination and collaboration procedures need to be established to process and archive existing data sets, and make them available to researchers, if possible through the means of the Internet.
- Important lessons have been learned from the post-tsunami field surveys. There is great need to continue the support of International Tsunami Survey Teams in future events.
- There is much to learn from areas prone to underwater landslides before failures actually occur. It is recommended to identify specific sites and to document and instrument those sites. Possible sites could include offshore Santa Barbara, California. Documentation includes bathymetry, seafloor morphology, coring and boring activities, and evaluation of gas hydrate stability. Instrumentation includes sensors measuring water pressures within the sediments, and strong ground motion on seafloor. In those specific sites, hydrodynamic modeling could be used to assess the tsunamigenic potential of these underwater landslides before they actually occur.
- Workshops should be planned in the future, gathering participants from the fields of hydrodynamics, marine geology, earthquake and engineering seismology, and

geotechnical engineering. They should also call upon local, federal and state agencies, oil and gas producers, insurance companies, and operators of port facilities, to present their views and to help formulate global plans of actions to mitigate landslide tsunami hazards.

- There is a need for producing hazard maps that delineate coastal areas hosting potential underwater landslides, and the shorelines that may be at risk from tsunamis generated by these potentially unstable areas. These preliminary, and possibly conservative, assessments of risks associated with underwater landslide tsunamis should assist in planning marine surveys of coastal areas exhibiting tsunamigenic potentials. These hazards maps could be improved based on probability distributions of landslides and tsunami events, and observed landslide and tsunami recurrence rates. Such information will be useful for risk analyses of landslide tsunamis, hazard mitigation and preparedness countermeasures, and port survivability studies.
- Research on underwater landslide hazards is a new interdisciplinary discipline, which involves several existing programs at NSF. An effective research program on the mitigation of underwater landslide hazards requires a concerted contribution from concerned NSF programs and other federal and states agencies.

5. Conclusions

Landslide tsunamis pose definite hazards to populations and industrial developments, notably along the West Coast of the United States. These hazards are not hypothetical but real as demonstrated by the 1998 Papua New Guinea catastrophe. Unfortunately, they are not fully understood and their potential cannot be as yet adequately ascertained. There is an immediate need for research to be coordinated and performed in order to improve our understanding of these phenomena and to plan countermeasures for mitigating their effects.

Intended to serve as a platform to build upon, this volume summarizes the state-of-the-art knowledge on underwater landslide tsunami hazards from the perspectives of earthquake and engineering seismology, geotechnical engineering, marine geology, and hydrodynamics. These various fields of engineering and science offer new synergetic opportunities for improving our understanding of landslide tsunamis. We hope that this volume will help to assemble interdisciplinary interactions and collaborations and will play a role in advancing our understanding of landslide tsunamis, and thus contribute to building a safer coastal environment.

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