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CONTRIBUTION OF ASTEROID GENERATED TSUNAMI TO THE IMPACT HAZARD

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Abstract

The long-standing uncertainty about the importance of asteroid-generated tsunami was addressed at a workshop in August 2016, co-sponsored by NASA and NOAA. Experts from NASA (Ames, JPL), NOAA, DoE (LLNL, SNL, LANL), DHS, FEMA, and academia addressed the hazard of tsunami created by asteroid impacts, focusing primarily on impacting NEAs with diameter <250m. Participants used modern computational tools to examine near-field wave generation by the impact; long-distance wave propagation; damage from coastal run-up and inundation, and associated hazard. The workshop resulted in broad consensus that damage from asteroid generated tsunami in this size range is primarily confined to near-coastal impacts, and that their contribution to the global ensemble impact hazard is not as great as previously thought.

Introduction

One of the most important uncertainties in addressing the global asteroid impact hazard has been lack of good models for the waves generated by ocean impacts, their propagation, and the associated damage when they reach the shore. These waves are generally called tsunami, although they differ in important ways from the well-know seismic tsunami, with some properties more similar to meteo-tsunami. This uncertainty about the importance of asteroid-impact tsunami was addressed at a workshop in August 2016, co-sponsored by NASA and NOAA. Experts from NASA (Ames, JPL), NOAA, DoE (LLNL, SNL, LANL), DHS, FEMA, and academia addressed the hazard of tsunami created by asteroid impacts, focusing primarily on impacting NEAs with diameter <250m. Program managers in attendance were Lindley Johnson, NASA Planetary Defense Coordination Office Executive, and Michael Angrove, NOAA Tsunami Program Manager. Conference organizers and chairs were David Morrison and Ethiraj Venkatapathy of the NASA Ames Asteroid Threat Assessment Project. A summary of the workshop has been published as NASA/TM-219463, January 2017. All of the talks presented at the workshop can be accessed on-line at https://tsunami-workshop.arc.nasa.gov/workshop2016/sched.php

The workshop was organized into three sessions: 1) Near-field wave generation by the impact; 2) Long distance wave propagation; 3) Damage from coastal run-up and inundation, and associated ensemble impact hazard. Workshop approaches were to compare simulations to understand differences in the results and gain confidence in the modeling for both formation and propagation of tsunami from asteroid impacts, and to use this information for preliminary risk assessment. Both airbursts and water impacts were considered. Participants jointly identified key issues and shared information in advance to coordinate discussion at the workshop and to understand differences in the results obtained with different simulation codes. The workshop resulted in a broad consensus that the asteroid impact tsunami threat is not as great as previously thought (as stated by the 2003 NASA Science Definition Team SDT Report), and that airburst events in particular are unlikely to produce significant damage by tsunami.

Session 1

The charge to Session 1 was to model the tsunami-producing potential of airbursts and direct water impacts, and to evaluate the nature of the waves produced. The approach was to model specific airburst cases (energy 5MT, 100MT, and 250MT, corresponding to approximate diameters for stony asteroids of 50m, 125m, and 180m) and also cratering impacts in shallow and deep water. The session organizer was Mark Boslough (Sandia National Labs/DoE), and the discussion panel chair was Bob Weaver (Los Alamos National Lab/DoE). The speakers were Boslough, Galen Gisler (Los Alamos National Lab/DoE), Michael Aftosmis (NASA Ames), and Darrel Robertson (NASA Ames).

The results presented reflect a major improvement in computing capability and code complexity over the models used for the 2003 NASA SDT analysis. Simulations were compared using a variety of both 2D and 3D codes. The most sophisticated hyrocodes required supercomputer runs of weeks. The Cart3D code was used to evaluate the effects of atmosphere energy deposition based on the NASA fragment-cloud model and angle-of-attack effect that result in non-circular surface damage footprints. The speakers agreed that for both airbursts over water and water impacts with energies of 5MT, 100MT, and 250MT, the resulting waves would not travel long distances. For a given energy, airbursts were less effective in generating waves, but in both airburst and impact cases, the waves formed are essentially circular (unlike a typical seismically generated tsunami) and dissipate rapidly due to the localized nature of the source and the turbulence of the wave. Local damage from impacts into the water may be similar to the cases of landslides into fjords, but these disturbances do not travel far. The potential for severe damage from asteroid generated tsunami over the energy range studied is therefore limited to impacts near the shore, and even in these cases the air blast, fireball, and possible ejection of sediment in shallow water areas may exceed the damage from the wave.

The airbursts modeled, most of which assumed an explosion altitude of 10 km, produced a wave from blast over-pressure. Most of the models did not explicitly consider other explosion altitudes or combined effects of airburst and solid impact on the water. Also not modeled were possible coupling mechanisms that might contribute to wave formation, such as steam explosions, plume ejection and collapse. It is not expected that these effects will substantially change the conclusions, but they deserve further consideration. While there may be conditions under which dangerous waves can be generated (e.g. airburst over very deep water or impact very near shore), the probability of such events is relatively small and therefore they do not significantly contribute to the ensemble hazard. There was a solid consensus among the workshop attendees that impact far from shore of asteroids <250m do not endanger coastal populations and infrastructure.

Session 2

The charge to Session 2 was to determine the ability of near-field impact-produced waves (from Session 1) to propagate over large distances, in deep and shallow water. Since propagation depends on several variables, including size and shape of the wave, distance of travel, and specific bathymetry along the path, multiple examples are needed to allow some generalizations.

The session organizer was Marsha Berger (New York University), and the discussion panel chair was Robert Weiss (Virginia Polytechnic Institute and State University). The speakers were Berger, Souheil Ezzedine (Lawrence Livermore National Lab/DoE), and Vasily Titov (Pacific Marine Environmental Lab/NOAA). Robert Weiss also contributed some model computations. The sites chosen for comparison were the South China Sea, the city of Westport on the coast of Washington, and the Long Beach area in southern California.

The major uncertainty in the presentations in Session 2 concerned the applicability of different computer codes to the propagation of waves described by Session 1. Berger used a computationally efficient code called GeoClaw that solves the Nonlinear Shallow Water Equations, which gives somewhat different results from the more complex Boussinesq codes used by Ezzedine and Weiss. Titov discussed shallow water codes and also results from the NOAA models for predicting the effects of seismically generated tsunami, but he did not present results for the shorter-wavelength waves from impacts. Due to differences in implementation, fidelity, and boundary conditions, detailed code comparisons were not possible. Although there were differences in the models, the consensus was that the waves that reached the shore as a result of airburst cases were not significantly different from one another. Only Berger discussed results from the South China Sea, but all of the speakers presented results for the Westport and Long Beach locations.

These models showed that the shorter wavelength waves produced from asteroid airburst or surface impact do not travel for great distances and that they also produce less inundation and flooding when they reach the shore. For these waves, the wave height is not a good measure of the potential damage; we must consider how much water is actually moving. The panelists found it very difficult to produce major inundations even with large (250MT) airbursts near shore. In the case of Westport, the modest 4m ridge between the city and the sea was not overtopped, although considerable damage was done to the boat harbor. Long Beach, with its very shallow slope, is more vulnerable, but even here a 250MT airburst 18 km from shore does not top the seawall and lead to major inland flooding. One uncertainty, however, concerned the inability of these codes to resolve in detail the interaction of waves with seawalls and other obstacles, including possible focusing effects.

Session 3

The charge to Session 3 was evaluation of the threat to human life and infrastructure posed by asteroid-generated tsunami. The presentations overlapped those of Session 2 in examining the inundation and damage from waves for specific locations, but with more detailed damage estimates. The ultimate product was a model for the contribution of asteroid water impacts to the ensemble impact hazard.

The session organizer was Donovan Mathias (NASA Ames), and the discussion panel chair was Steve Chesley (NASA JPL). The speakers were Vasily Titov (Pacific Marine Environmental Lab/NOAA), Randy LeVeque (University of Washington), Barbara Jennings (Sandia National Labs/DoE), Cynthia McCoy (FEMA/DHS), Lorien Wheeler (NASA Ames) and Mathias. Guest speaker Shunichi Koshimura (Tohoku University, Japan) provided perspective from the 2011 Tohoku earthquake tsunami.

Titov and LeVeque described inundation model results from asteroid impact or seismic events, respectively. Titov showed that very large (250 MT) airburst events could, in some cases, lead to significant inundation at isolated locations even hundreds of km from the airburst due to wave focusing effects. Leveque demonstrated the effectiveness of GeoClaw for modeling inundation from seismic events, but did not explicitly model the kind of waves produced from asteroid impacts.

Jennings and McCoy discussed detailed analyses of the economic and human costs of two hypothetical tsunami events. Jennings focused on the economic effects of a 250 MT airburst over the ocean near Long Beach, using the Department of Homeland Security tool called FASTMap, which allows quick identification of key infrastructure elements. McCoy explored the possible effects of an asteroid impact tsunami using HAZUS, a FEMA tool that is in development and used to estimate the effects of various natural disasters. She emphasized the need for properly reinforced construction techniques to mitigate the damage from a tsunami inundation, and the importance of evaluating evacuation times and routes.

Wheeler and Mathias presented perspectives on the ensemble risk based on NASA Ames “engineering models”. Mathias concluded that the current assessment of the asteroid impact hazard is substantially reduced relative to the best understanding from a decade ago. He noted that the modeling results presented earlier in the workshop consistently showed less efficient coupling of the impactor energy into wave production, and lower damage from short-wavelength waves. The ensemble hazard assessment concluded: (1) The impact tsunami hazard is negligible for asteroid diameters below 200m. (2) For asteroids larger than about 300m, the risk peaks at about an order of magnitude lower casualty rate than the land impacts. (3) Larger than about 500m the global risk (based on previous work) dominates over either land or ocean impact. (4) The *average* annual casualties from land and ocean impacts (not including global effects) are in the range of 1-10. These conclusions concerning the global ensemble hazard were used by the 2018 NASA Science Definition Team (SDT) study of the requirements for improved asteroid detection and hazard mitigation, sponsored by the NASA Planetary Defense Coordination Office.

Workshop Summary Discussion

The workshop concluded with a general discussion moderated by Steve Chesley (NASA JPL). These summary comments are drawn from that and other discussions throughout the workshop.

Individual vs. ensemble risk. There is an important difference between the treatment of risk from individual impacts with specified targets, and the ensemble risk from the entire asteroid population. Individual cases require detailed knowledge (or assumptions) about the nature of the impactor and the target, taking into account ocean bathymetry, shore configuration, breakwaters, and distribution of infrastructure and population. Evaluation of the global ensemble hazard, in contrast, is based on weighted averages over a wide range of conditions, which can be estimated with less precise engineering models. One of the objectives of this workshop was to investigate what level of precision is needed to move from individual cases to the global ensemble risk.

*People affected vs. casualties vs. damage***.** There is no uniform, accepted approach for how to estimate the cost associated with asteroid impact tsunami. In the 2003 SDT, inundation was used to estimate the number of people affected, with no attempt to determine the number or cost of actual casualties. Some subsequent estimates of tsunami casualties have arbitrarily assumed, based on the likelihood of some warning, that 10 percent of the affected population would be killed, with the other 90 percent “wet and angry”. More detailed FEMA and DHS tools discussed at the workshop can provide infrastructure damage estimates for specific scenarios, but cannot effectively be used to understand the ensemble risk. It is important when discussing impact hazards to state clearly what metrics are being used.

Actuarial approach vs. focus on catastrophic events. A recurring issue within the impact hazard community is the challenge of properly analyzing and communicating the impact threat. Traditionally, the metric used has been average annual fatalities, a metric that does not convey the rarity or severity of catastrophic events. As an illustration, asteroids may kill 100 people per year on average, but this derives mostly from events affecting a million people on 10,000-year intervals. That is clearly not the same thing as, *e.g*., commercial airline crashes, which may have a comparable annual fatality rate that is actually realized year after year. The contour-style hazard plots presented by Mathias and Wheeler help to quantify the episodic, catastrophic threat posed by asteroid impacts and thus represent a new and useful tool for decision makers.

Characterizing uncertainties. To get from an impact flux to a damage rate for either ocean or land impacts, there is a long chain of modeling challenges. Uncertainty estimates are more important for evaluating individual threats than for estimating the ensemble risk. In either case, estimates of uncertainty need to be communicated to stakeholders and decision makers.

Workshop Conclusions and Recommendations

The Workshop on Asteroid Generated Tsunami achieved its primary goals of re-evaluating the tsunami risk from impacts by small (<250m diameter) asteroids using modern codes and simulations, and providing a better estimate of the ensemble risk from water impacts.

Any evaluation of impact hazards requires knowledge of the population of impacting asteroids. Recent work on population has shown that the impact frequency once identified for asteroids a few hundred meters in diameter was too high, and that the overall impact frequency for asteroids in the range 30-300m is about a factor of three lower than once assumed. This is a contributing factor in the lowering of the tsunami threat relative to that estimated for the 2003 SDT report.

Airbursts over water are not likely to generate substantial tsunami-like waves. The waves generated by water impacts are quite different from seismically generated tsunami, having shorter wavelength and higher turbulent dissipation. There was a broad consensus that the tsunami threat is not as great as previously thought (as stated by the 2003 NASA SDT Report), but there are variations in the degree of confidence among the participants because of the limited number of cases that were modeled and the possibility that we have missed something important.

In the case of airbursts and surface impacts from objects less than about 250m diameter, most damage to coastal populations is limited to impacts close to the shore, in which case the direct blast damage may be more important than the wave generated. Detailed evaluation of the inundation is highly dependent on the near-shore bathymetry and shore configuration; these effects generally require higher resolution models than those used in the workshop. The risk from near-shore impacts can be important for considering individual cases, but they do not contribute significantly to the ensemble hazard.

Recent Publications, Relevant to the Workshop

Aftosmis, M., Mathias, D., Nemec, M., Berger, M.: “Numerical simulation of bolide entry with ground footprint prediction”. *AIAA-2016-0998* (2016).

Berger, M. and Goodman, J.: “Air-burst generated tsunamis”. *J. Pure and Applied Geophys* (2017, submitted).

Boslough, M.: “Airburst-generated tsunami by various coupling mechanisms”. IAA Planetary Defense Conference 2017.

Ezzedine, S.M.: “Simulation of PDC2017 asteroid entry, water impact, hazard and consequences on Japan’s east and west coasts”. IAA Planetary Defense Conference 2017.

Gisler, G.: Tsunami simulations. *Annual Rev. Fluid Mech.* 40, 71-90 (2008).

Gisler, G., Weaver, R., Gittings, M.: Calculations of asteroid impacts into deep and shallow water. *Pure Appl. Geophys*. 168 , 1187-1198 (2010).

Gisler, G.: "What Would Happen if a Giant Asteroid Struck the Ocean". AGU 2016 presentation and http://gizmodo.com/heres-what-would-happen-if-a-giant-asteroid-struck-the-ocean1790084340.

Gisler, G.: "Three dimensional simulations of oblique asteroid impacts into water". IAA Planetary Defense Conference 2017.

Harris, A.W. and D'Abramo, G.: "The population of near-earth asteroids." *Icarus* 257, 302-312 (2016).

Harris, A.W.: "NEA population and current survey status". IAA Planetary Defense Conference 2017.

Mathias, D. L., Wheeler, L. F., Dotson, J. L.: A Probabilistic Asteroid Impact Risk Model: Assessment of Sub-300 m Impacts, Icarus 289C 106-119 (2017)

Mathias, D. L., Wheeler, L., Dotson, J. Aftosmis, M. and Tarano. A.: "Ensemble Risk Assessment in Support of the 2016 NEO Science Definition Team", IAA Planetary Defense Conference 2017.

Melosh, H.: Impact-generated tsunamis: An over-rated hazard. In: 34th Lunar and Planetary Sciences Conference (Abstract, 2003).

Morrison, D. and Venkatapathy, E.: Asteroid Generated Tsunami: Summary of NASA/NOAA Workshop, NASA TM-219463 (January 2017)

Robertson, D., Wheeler, L., and Mathias, D.: "Comparison of damage from hydrocode simulations of an asteroid airburst or impact on land, in deep, or in shallow water." IAA Planetary Defense Conference 2017.

Rumpf, C., Lewis, H., and Atkinson, P.: "Asteroid impact effects and their immediate hazards for human populations". *Geophys. Res. Letts* (2017, in press).

Weiss, R., Wunnemann, K., Bahlburg, H.: Numerical modelling of generation, propagation and run-up of tsunamis caused by oceanic impacts: model strategy and technical solutions. *Geophys. J. Intl*. 167 , 77-88 (2006).

Wheeler, L. F, Register, P. J., and Mathias, D. L.: "Fragment-cloud model for asteroid breakup and atmospheric energy deposition", *Icarus* (2017, in press).

Wheeler, L. F. and Mathias, D. L.: "Modeling the atmospheric breakup of varied asteroid structures: inference for the Chelyabinsk meteor and risk assessment. (2017, in press)