LA-UR- 01 - 4764

54
71

~~LA-UR-00-~~

c. /

Approved for public release;
distribution is unlimited

Title: TSUNAMI FROM ASTEROID AND COMET IMPACTS

Author(s): Jack G. Hills* (T-6), M. Patrick Goda (T-6), Charles Mader (T-14), and Mike Warren (T-6)

Submitted to: DOE Office of Scientific and Technical Information (OSTI)

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

TSUNAMI FROM ASTEROID AND COMET IMPACTS

Jack G. Hills* (T-6), M. Patrick Goda (T-6), Charles Mader
(T-14), and Mike Warren (T-6)

Abstract

Tsunami may produce most of the economic damage in large asteroid impacts. They may be the principal cause of post-impact deaths in developed countries with long coast lines. We have determined regions of Earth that are most susceptible to asteroid tsunami by simulating the effect of a large asteroid impact into mid-ocean. We have modeled the effect of midAtlantic and midPacific impacts that produce craters 300 and 150 km in diameter. A KT-size impactor would cause the larger of these craters. We find that the larger of these two midAtlantic impacts would engulf the entire Florida Peninsula. The smaller one would inundate the eastern third of the peninsula while a tsunami passing through the Gulf of Cuba would inundate the West Coast of Florida. Impacts at three different sites in the Pacific show the great vulnerability of Tokyo and its surroundings to asteroid tsunami. Mainland Asia is relatively protected from asteroid tsunami due to a broad continental shelf. In Europe, the Iberian Peninsula and the southern part of the Atlantic Coast of France are highly vulnerable to asteroid tsunami.

Background and Research Objectives

Asteroid and comet impacts are the single greatest known threat to the survival of humanity and even life on Earth. Hills and Goda (1993) were the first to systematically determine the types and amounts of damage expected from asteroid impacts. They found that one of the most serious consequences of such impacts is tsunami if a large asteroid or comet impacts the ocean.

Our research goal in this LDRD project was to use Los Alamos computer capabilities and professional expertise to better determine the impact energy deposited into the water by impactors of arbitrary mass in arbitrary approach orbits. We would then determine the tsunami run-ups expected from such encounters.

*Principal Investigator, e-mail: jgh@lanl.gov

We were motivated to reduce the threat from asteroid impacts both by providing a risk assessment of the amount of damage expected from such an impact, which will determine the appropriate amount to spend on efforts to prevent or mitigate such disasters, and to identify coastal areas that are particularly vulnerable to such impacts.

We planned to use simulations of large asteroid impacts in mid ocean to identify coastal areas that are most vulnerable. We planned to find the range of damage in these vulnerable areas, such as Florida and Long Island, over a span of time by making Monte Carlo simulations of impacts in the ocean over the distribution of asteroid sizes that are expected to impact the ocean over that time.

Importance to LANL's Science and Technology Base and National R&D Needs

Asteroids can be deflected from Earth impact. The most economical way to do it is to use nuclear explosives to eject off part of the asteroid so the remainder of the asteroid recoils in the opposite direction like a rocket. LANL is likely to play a significant part in any attempts to deflect asteroids from impact. This was recognized when a Congressionally mandated meeting on asteroid mitigation was held at Los Alamos in January, 1992.

One factor that policymakers must consider before deciding whether to implement any system to deflect asteroids is the cost of the damage relative to the cost of implementation. We address this question by looking at tsunami generated in impacts since they are likely to cause the most economic damage. Most deaths due to impacts of large asteroids will likely occur in underdeveloped countries as the result of mass starvation. This results from crop failure due to the impacts ejecting much dust into the atmosphere, which may keep Earth in near total darkness for months. However, this dust is not likely to destroy the economic infrastructure (buildings, roads, railroads, airports, etc.) A tsunami carries a considerable load of debris and typically inundates an area in a series of waves. The scouring of the land by this debris can knock down buildings and other structures reducing coastal areas to mudflats.

Unless these flooded areas can be evacuated in sufficient time, it is very likely that the majority of people living in them will die. Tsunami may actually kill more people in developed countries with large coast lines, such as the United States than any other effect of an asteroid-comet impact. In this project we address the question of the expected amount of tsunami flooding from asteroid impacts.

Scientific Approach and Accomplishments

The first part of our work was to better model the fragmentation of an asteroid in the atmosphere to determine more accurately the energy at which it impacts at sea level. This improved upon the model in Hills and Goda (1993) by using a spherical rather than a flat atmosphere, so we could allow for collision at very steep angles to the atmosphere and even grazing atmospheric encounters. We used this model to estimate not only the tsunami damage, but also that from cratering, earthquakes, fires, and blastwaves. The results were published in a refereed journal (Hills and Goda 1998).

The second (and most important) part of this work was to model the flooding expected when large asteroids impact in the middle of the ocean. This work was to be used to determine the areas of greatest vulnerability.

The simulation of the run-ups by large impactors allows us to find areas of Earth that are particularly sensitive to asteroid tsunami. We then planned to investigate how sensitive these areas are to the multitude of small impacts that occur between the large ones.

The wavelengths of tsunami produced by larger asteroids are long enough that wave dispersion is not a problem. We can model these tsunami accurately using the shallow water (or long-wavelength) approximation. We initially used the SWAN code (Mader 1988) for these calculations. The maximum running time of the code was limited by instabilities at the boundaries. M.P. Goda rewrote the SWAN code in the computer language C and improved the graphics package for displaying tsunami runups.

This SWIM (Shallow Water Inundation Model) code was tested against results from the original SWAN code to assure its accuracy. The boundary conditions were later improved to allow us to run the code for times much longer than permitted by SWAN. The improvements allowed us to run it for times that are at least twice as great as the tsunami travel time across the major ocean basins.

The improved code has allowed us to dispense with the use of the piston, which was necessary in the original code. We simply start with the initial crater and allow the computations to proceed until the elapsed time is at least twice the time required for tsunami to travel across the given ocean basin. We find that these long running times are necessary because reflection of tsunami waves off continents and island chains can cause noticeable enhancements in the tsunami runups in certain locales.

We made simulations with impact craters 150 km and 300 km in diameter in the Atlantic at (Long.,Lat.) = (40° W, 35° N). We also made simulations in the Pacific with craters of these two sizes. These simulations were done for three different impact points: (Long., Lat.) = (170° W, 35° N), (138.25° W, 27.75° N), and (169.75° E, 28.75° N). The Atlantic and Pacific impact sites are shown in Fig. 1. We estimate that a water crater 300 km in diameter would be produced by a K-T size impactor about 10 km in diameter while one 150 km in diameter would be produced by an object with half that diameter. The probability of the larger impactor hitting in a given year is about one in a 100 million while the probability of the smaller impactor hitting in a given year is about 1 in 10 million. In these simulations the topographical ocean depth is determined from ETOPO5 (from US Defense Mapping Agency). This gave a grid with a topographical resolution of 5 arc minutes. We had planned to make runs with 2 arc minutes of resolution in the final year of this project but funding termination at the end of the second year prevented it.

Atlantic Impacts

Fig. 2 shows the maximum wave height within the Atlantic Ocean as the tsunami propagates away from the 150-km diameter crater. We note that some of the tsunami energy is funneled south along the western edge of the midAtlantic Ridge.

There is also a tongue of high water that moves towards Florida. This is due to an absence of seamounts in that direction to reflect back the energy. We also note the shoaling as the tsunami hits the continental shelf. This provides good protection for the most northern part of the United States and for the Atlantic providences of Canada. It also provides good protection for the British Isles and the European Coast east of it. We note the lack of protection by continental shelves in the southern Atlantic Coast of France, the Iberian Peninsula, and the Atlantic Coast of Africa.

As we might guess from the previous plot, the most significant flooding in Europe occurred along the south Atlantic Coast of France and the Iberian Peninsula. Fig. 3 shows the depth of inundation along the Atlantic Coast of France and Fig. 4 shows it for the Iberian Peninsula. The depth is shown in meters above local ground level for the simulations with craters 150 and 300 kilometers in diameter. The depth of inundation in France is not as great as it is along the Iberian Peninsula where the depth reaches over 200 meters for the larger crater and 100 meters for the smaller one, but the distance the flood moves inland in France is much greater due to the lack of mountains to contain it.

The damage is greater in North America than in Europe. The major difference between the results of the new simulations and that of the earlier one (Hills and Mader 1997) is the degree of flooding of the Florida Peninsula. Fig. 5 shows the maximum flooding produced by with craters 150 and 300 km in diameter. The figures show the maximum depth of inundation above local ground level at each point on the peninsula. We find much more profound flooding as the result of our being able to run the code for a much longer time than was possible in Hills and Mader (1997). The tsunami from the larger crater inundates all of Florida. The tsunami from the smaller one inundates the eastern third of Florida while the part of it that passes through the straits between Florida and Cuba causes additional flooding on the West Coast of Florida. The depth of inundation of the East Coast exceeds 100 meters in some places for the larger crater.

We find that two factors are responsible for this late-stage flooding in Florida: The considerable slowing down of the tsunami as it enters the shallows off Florida causes a mesa of water to slowly build up on this shelf. Then a second tsunami wave reflects off the Bahamas chain and piles up on top of the now much deeper water left by the passage of the first tsunami wave. When this mesa of water collapses, it produces the Florida flooding.

Pacific Impacts

Fig. 6 shows the highest water reached as the tsunami travels away from the centermost of the three impact sites in the Pacific for a 300-km diameter crater. We see the significant protection afforded by the Aleutian Islands and the continental shelf off Asia. China and most of mainland Asia is relatively protected by the extensive continental shelf. Japan has no significant continental shelf, so the tsunami slams directly into it. A similar situation occurs along the West Coast of the United States. The West Coast is much more prone to tsunami flood than mainland Asia.

Fig. 7 shows the depth of tsunami flooding in Japan as a result of the tsunami given in Fig. 6. The plains around Tokyo are particularly prone to tsunami flooding.

The run-up simulations for the West Coast of the United States does not look as bad as that for Japan, principally because the coastal mountains restrict the flood to a narrow zone around the coast. However, major cities are in this narrow coastal band. Fig.~8 shows the depth of inundation in the Pacific Northwest for the eastern most of the three Pacific impact sites. This is done for the two different crater sizes. The tsunami tends to go up to the coastal mountains. We note the penetration of the tsunami up some of the major river valleys in this region. The apparent tranquil state in Seattle may be due to numerical limitations. The grid resolution may not be good enough to accurately model the passage of the tsunami wave through the straits between Vancouver Island and Washington State.

We planned to improve the resolution by moving onto a 2-minute grid. This was to be increased to 1-minute resolution when this data become available. This work would have required the use of a massively parallel computer, which we have available at Los Alamos. The cut off of third-year funding prevented our doing this work.

Concluding Remarks

It is difficult to imagine trying to manage by normal civil defense procedures the catastrophes produced by asteroid impacts because of the large scale of the damage and short timescales involved. It would be far better to detect these objects well before they impact Earth. This will allow much more time for response. There should be a civil defense response to the degree that it is feasible. There also should be an active defense to assure that these larger impactors never hit the ground. Such defense is possible. We believe that it should be implemented.

The project was ended abruptly at the beginning of its third year as a result of the Congressional rescissions of LDRD funding. The abrupt ending allowed only publication of progress reports on the work of the two funded years.

Several parts of the project were highly advanced but not far enough along to produce publications by the time that we were required to cease work on the project: We were modeling the propagation of tsunami waves from small craters. These models require the full Navier Stokes equations to allow for wave dispersion over distances comparable to that of the large ocean basins, unlike the case for waves from the large craters, which suffer very little dispersion in going across these basins. These models of tsunami propagation from small craters would have been put into a code to simulate the range of tsunami damage in vulnerable areas such as Long Island over a long period of time. These small impactors do much less damage individually, but there are many more of them, so their collective damage may be greater for areas close to the coast. We also were not able to complete work on the initial formation of the crater in the water using a Smooth-Particle-Hydrodynamics (SPH) code.

The code was well along with the proper equations of state of water and underlying rock put into it. We were ready to start the simulations in the third year. This would have given us a much better idea of the size of the crater produced by impactors of various mass and impact velocity.

Publications

Hills, J.G. and Mader, C.L., 1997, in **Near-Earth Objects, *Annals of the New York Academy of Sciences*, 822**, 381-394 "Tsunami Produced by Impacts of Small Asteroids".

Hills, J.G. and Goda, M.P. 1998, *Planetary and Space Science* 46, No. 2/3, 219-229, "Damage from the Impacts of Small Asteroids".

Hills, J.G., Goda, M.P., Mader, C.L. and Warren, M.S. 1998, *Annales Geophysicae. Part IV. Nonlinear Geophysics and Natural Hazards*, 16, C1164, "Tsunami from Asteroid and Comet Impacts: The Vulnerability of Europe".

Hills, J.G., Goda, M.P., Mader, C.L., and Warren, M.S. 1998, *Bulletin American Astronomical Society* 29, 1260, "Down-to-Earth Astronomy: Tsunami from Asteroid-Comet Impacts".

Hills, J.G. and Goda, M.P. 1998, *Science of Tsunami Hazards* 16, 3-10, "Tsunami from Asteroid and Comet Impacts: The Vulnerability of Europe".

Hills, J.G. and Goda, M.P. 1999, *Physica D* 133/1-4, 189-198, "Damage from Comet-Asteroid Impacts with Earth".

Hills, J.G. and Goda, M.P. 2001, *Science of Tsunami Hazards*, 19, 55-65, "The Asteroid Tsunami Project at Los Alamos National Laboratory".

References

Hills, J.G. and Goda, M.P. 1993, *Astronomical Journal* 105, 1114-1144, "The Fragmentation of Asteroids in the Atmosphere".

Mader, C.L. 1988, *Numerical Modeling of Water Waves* (University of California Press, Berkeley).

Figure Captions

Figure 1. Positions of the four impact sites used in our models.

Figure 2. Maximum wave height above sea level reached at each point in the Atlantic Ocean as a result of the 150-km diameter crater produced by the impactor. The gray scale gives the height in meters at each location.

Figure 3. The depth of inundation along the Atlantic Coast of France as a result of the formation of a 150-km and 300 km impact crater in the middle of the Atlantic Ocean. The gray scale gives the maximum local flood depth in meters above mean ground level.

Figure 4. Same as Figure~3 except it shows the Iberian Peninsula.

Figure 5. Same as Figure~3 except it shows the Florida Peninsula.

Figure 6. Maximum wave height above sea level in the Pacific due to the formation of an impact crater 300 km in diameter at the centermost of the three Pacific impact sites shown in Figure~1.

Figure 7. The maximum inundation depth in Japan due to the tsunami showed in Figure 6.

Figure 8. The maximum inundation on the Pacific Northwest Coast of the United States due to an impact at the easternmost of the three impact sites in the Pacific. The plot shows the maximum depth of flooding above local ground level at each point for impact craters 300 and 150 km in diameter.

Figure: The figures can be found at the following URL,
<http://qso.lanl.gov/~mpg/jack/LDRD.html>

Fig #1

hole25min: 150km Diam. Crater, Max Wave Height (m)

GRDS: 00LA/000

1999-12-11-20 33

#2

26

Coastal Inundation, Iberian Peninsula (m) AGL

[atl_150] Atlantic Ocean Impact: 150km Diameter Crater, (40W,35N)

#4a

Coastal Inundation, Iberian Peninsula (m) AGL

[atl_300] Atlantic Ocean Impact: 300km Diameter Crater, (40W,35N)

H / b

#5a

#5b

Pacific1: 300km Diam. Crater, Max Wave Height (m)

GRIDS: GOLA/IGES

1999-05-11-20:29

6

Coastal Inundation, Japan (m) AGL

[pac1_150] Pacific Ocean Impact: 150km Diameter Crater, (170W,35N)

7a

Coastal Inundation, Japan (m) AGL

[pac1_300] Pacific Ocean Impact: 300km Diameter Crater, (170W,35N)

7b

8a

86