IMPACT-GENERATED TSUNAMIS: AN OVER-RATED HAZARD. H. J. Melosh, Lunar and Planetary Lab, University of Arizona, Tucson AZ 85721 (jmelosh@lpl.arizona.edu).

Introduction: A number of authors [1, 2] have suggested that oceanic waves (tsunami) created by the impact of relatively small asteroids into the Earth's oceans might cause widespread devastation to coastal cities. If correct, this suggests that asteroids > 100 m in diameter may pose a serious hazard to humanity and could require a substantial expansion of the current efforts to identify earth-crossing asteroids > 1 km in diameter.

The debate on this hazard was recently altered by the release of a document previously inaccessible to the scientific community. In 1968 the US Office of Naval Research commissioned a summary of several decades of research into the hazard proposed by waves generated by nuclear explosions in the ocean. Authored by tsunami expert William Van Dorn, this 173-page report entitled "Handbook of Explosion-Generated Water Waves" [3] affords new insight into the process of impact wave formation, propagation, and run up onto the shoreline.

Careful reading of the report suggests that previous work on impact-generated tsunami has exaggerated the hazard posed by such waves. One of Van Dorn's crucial points it that large explosions (and impacts) produce waves with periods in the range of 20 to 100 sec. This is between the ranges of 5 to 20 sec for storm-generated ocean swell and 100 sec to 1 hour for more common earthquake-produced tsunami. Thus, impact-generated waves lie outside the frequency range of familiar phenomena; our intuition from ordinary surf or earthquake tsunami is not a good guide to the behavior of these waves. In particular, large impact-generated waves can be expected to break on the outer continental shelf and produce little onshore damage. This phenomenon is known in the defense community as the "Van Dorn effect".

In the remainder of this abstract I summarize the basic points made by Van Dorn and discuss why some previous work on impact tsunamis has greatly overestimated the hazard in each of three basic categories.

Impact tsunami formation and propagation in the deep ocean: An impact or explosion in the ocean displaces a quantity of water. The displaced water piles up near the rim of the crater. After the cratering flow has ceased, the rim collapses and the crater is filled by the centripetal inflow of water from the rim and adjacent ocean. A wave then propagates away from the site of the disturbance.

There are two basic cases for impact wave generation. In the first, the ocean is much deeper than the cavity opened by the impact. In this case linear wave propagation theory is applicable and the evolution of the impact tsunami can be analyzed by well-established methods [4]. On the other hand, if the impact is so large that the excavated cavity exceeds the depth of the ocean, the ocean is temporarily cleared away from the site of the impact, the seafloor itself is cratered, and the ejected water falls onto the ocean surface. This case is much more difficult to analyze analytically and can probably only be addressed by hydrocode computations. At the moment, two recent hydrocode computations have given widely divergent results [5, 6]. However, because this limit is approached only by asteroids more than about 1 km in diameter, it is not relevant to the present hazard issue, which focuses on asteroids in the 100 to 1000 m size range (it is already agreed that asteroids greater than about 1 km diameter are a global threat [7]).

Because the volume of the rim and of the crater are approximately equal in the case when the initial crater is less deep than the ocean itself, their two effects tend to cancel one another, already limiting the size of the disturbance propagated from the impact site. This differs from an earthquake-generated tsunami in which the seabed either rises or sinks and a net volume of water is transported across a large area of the ocean [8].

An important point emphasized by Van Dorn, but evidently neglected in several publications [1, 2] is that, as the impact-generated waves propagates away from the impact site, *the wave amplitude can never exceed the depth of the ocean*. This elementary principle (actually, Van Dorn limits the wave height to 0.39 times the ocean depth) is enforced by the breaking and consequent energy dissipation of higher amplitude waves.

The group and phase velocities of waves propagating in water comparable in depth to their own wavelength are strongly dependent on the wavelength (See Fig. 1). The loner the wavelength, the faster the wave travels, up to the limit of very long waves whose speed is $\sqrt{gh_0}$, where g is the acceleration of gravity and h_0 is the ocean depth. Such waves are dispersed as they travel. Although the period of the dominant wave group is constant, the wavelength varies with water depth, as given by the dispersion relation between wavelength and period. The amplitude of the maximum height wave in the leading wave group declines as 1/(distance from the impact site). This decline is due equally to the effect of dispersion and of spreading of the energy over a larger area.

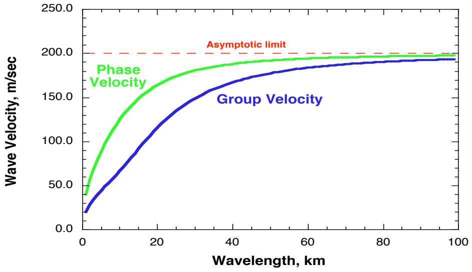

Figure 1. Group and phase velocities of ocean waves as a function of wavelength. Plot is constructed assuming an ocean 4 km deep, the average depth of Earth's oceans.

Shoaling of impact tsunami: As an impact-generated wave approaches shore, the decreasing water depth causes the wave amplitude to increase. The amplitude increase is commonly given by the shoaling factor, S, which depends on the wave period □ and water depth h. Since wave energy is proportional to wave amplitude squared, energy conservation requires that the shoaling factor equals the square root of the ratio of group velocity $v_g(\square, h_0)$ in water of initial depth h_0 to the group velocity in shallow water of depth h:

$$S = \square\frac{v_g(\square,h_0)}{v_g(\square,h)}\square^{1/2}$$

This shoaling factor is substantially smaller for impact-generated waves than for the very long-wavelength earthquake tsunami. Thus, whereas [1] cited shoaling factors of 10 to 20, based on experience with historical earthquake tsunami, [2, 9], using the full equation above, find much more moderate shoaling factors of less than 2, in agreement with the prescription of [3].

Breaking and run-in of impact tsunami: As waves approach shore, the water depth approaches zero and the shoaling factor above mathematically approaches infinity. In reality, the wave height increases until the wave becomes unstable and breaks, dissipating its energy in turbulent eddies. Previous work on impact tsunami has generally ignored wave breaking, but Van Dorn argues that it is of overriding importance in limiting the damage that explosion-generated waves can inflict on the coast. The very long-wavelength earthquake tsunamis almost never break: the water depth simply increases by the offshore shoaling factor and the run-in (the distance the water surges inland from the initial shoreline) is simply given by S cot □, where □ is the slope of the shore (assumed to be the same above and below mean sea level, for simplicity).

Normal ocean swell breaks within a few tens of meters of the shore, depending upon the slope of the bottom in the near-shore zone and the period of the breakers: As every surfer knows, long-period swells break farther from the shore than short-period chop. Impact and explosion generated waves are of much longer period than ocean swell (but not as long as earthquake tsunami) and break still farther from the shore: at the edge of the continental shelf, according to Van Dorn. In this case the run-in can be drastically smaller than S cot □. The resulting turbulent zone between the edge of the continental shelf and shore may be hazardous for coastal shipping, but little damage is expected for most onshore structures (local bottom topography may focus wave damage in harbors or along special stretches of the coast, but this damage is not general).

Conclusion: The release of the Van Dorn report has saved the impact community a great deal of effort in categorizing the impact tsunami hazard. It appears that the defense community has already determined that explosion-generated waves are neither a serious threat nor a promising weapon. Although more work is needed on impact-generated tsunami, it appears that such waves generated by asteroids in the 100 to 1000 m diameter range may not pose as great a threat as previously believed.

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