TWO- AND THREE-DIMENSIONAL SIMULATIONS OF ASTEROID OCEAN IMPACTS. G. Gisler, R. P. Weaver, C. L. Mader[1] and M. L. Gittings[2], [1]Los Alamos National Laboratory, MS T087, Los Alamos NM 87545 USA, [2]Science Applications International MS T087, Los Alamos NM 87545 USA

We have performed a series of two-dimensional and three-dimensional simulations of asteroid impacts into an ocean using the SAGE code from Los Alamos National Laboratory and Science Applications International Corporation. The SAGE code is a compressible Eulerian hydrodynamics code using continuous adaptive mesh refinement for following discontinuities with a fine grid while treating the bulk of the simulation more coarsely. We have used tabular equations of state for the atmosphere, water, the oceanic crust, and the mantle. In two dimensions, we simulated asteroid impactors moving at 20 km/s vertically through an exponential atmosphere into a 5 km deep ocean. The impactors were composed of mantle material (3.32 g/cc) or iron (7.8 g/cc) with diameters from 250m to 10 km. In our three-dimensional runs we simulated asteroids of 1 km diameter composed of iron moving at 20 km/s at angles of 45 and 60 degrees from the vertical. All impacts, including the oblique ones, produce large underwater cavities with nearly vertical walls followed by a collapse starting from the bottom and subsequent vertical jetting. The initial asymmetry of the oblique-impact transient crater does not persist beyond the first two minutes. Substantial amounts of water are vaporized and lofted high into the atmosphere. In the larger impacts, significant amounts of crustal material are lofted as well. Tsunamis up to a kilometer in initial height are generated by the collapse of the vertical jet. These waves are initially complex in form, and interact strongly with shocks propagating through the water and the crust. The tsunami waves are followed out to 100 km from the point of impact. Their periods and wavelengths show them to be intermediate type waves, and not (in general) shallow-water waves. At great distances, the waves decay faster than the inverse of the distance from the impact point, ignoring sea-floor topography.

A point of crucial interest is to determine the smallest asteroid for which widespread tsunami damage might be expected. To address this, we paid special attention to the wave heights generated by the vertical impacts we simulated, and the attenuation of these heights as a function of distance away from the impact point. We placed massless tracer particles on the water surface at the initial time and tracked their positions throughout the simulations. For the smaller impactors, the tracer particles executed roughly elliptical trajectories that almost (but didn't quite) close upon themselves. For the more massive impactors, the tracer trajectories were extremely complex and difficult to resolve into simple waves. Because the tracers tended to drift away from the surface, it was insufficient to track the maximum heights reached by the tracers. Instead, we measured the amplitudes of the maximum excursions from mean tracer-particle position as a function of distance from the point of impact. These amplitudes are plotted in Figure 1, where it is seen that for all six cases in our parameter study, the waves decay with distance r from the impact point faster than $(1/r)$. The power-law indices for the least-squares fits plotted vary from –2.25 to –1.3.

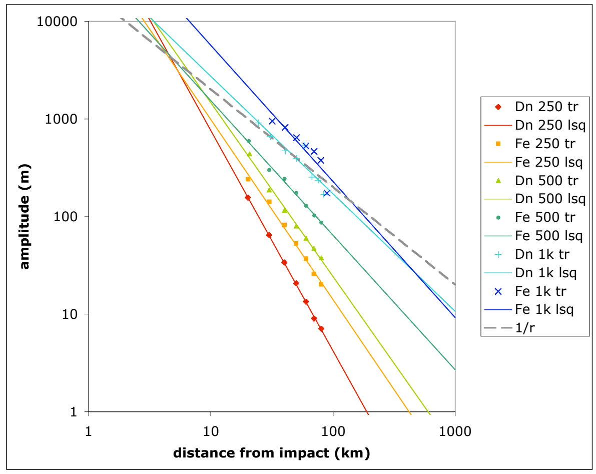

Figure 1. Tracer-particle amplitudes in asteroid-generated tsunami waves decline faster than the inverse of the distance from the impact point.

In all cases we investigated, the waves are extremely dissipative, compared to other types of tsunamis or other waves on water. The reason for this is that the perturbation giving rise to the waves, namely the impact of the asteroid and the immediate vaporization of the water along the path of entry, is hypersonic and a complex system of shocks is initiated in the water, the air, and the ocean floor basalt. The interaction of these shocks with each other and with the bounding surfaces (the air-water interface and the water-crust interface) keeps perturbing the waves that are generated so that the motion becomes, and remains, highly turbulent. This is illustrated in Figure 1, where we plot, in grayscale, density (top) and pressure (bottom) for a small portion of the computational domain near the leading wave, 34 kilometers distant from, and 5 minutes after, the impact event. Evident in the pressure plot is the highly turbulent, post-shock, atmosphere, which continues to extract energy from the propagating wave. Turbulence within the water gives rise to continued cavitation often (but not always) closely associated with the wave crests. In this frame we see the remnant of a collapsed cavitation bubble, together with the backward-propagating shock caused by its recent collapse.

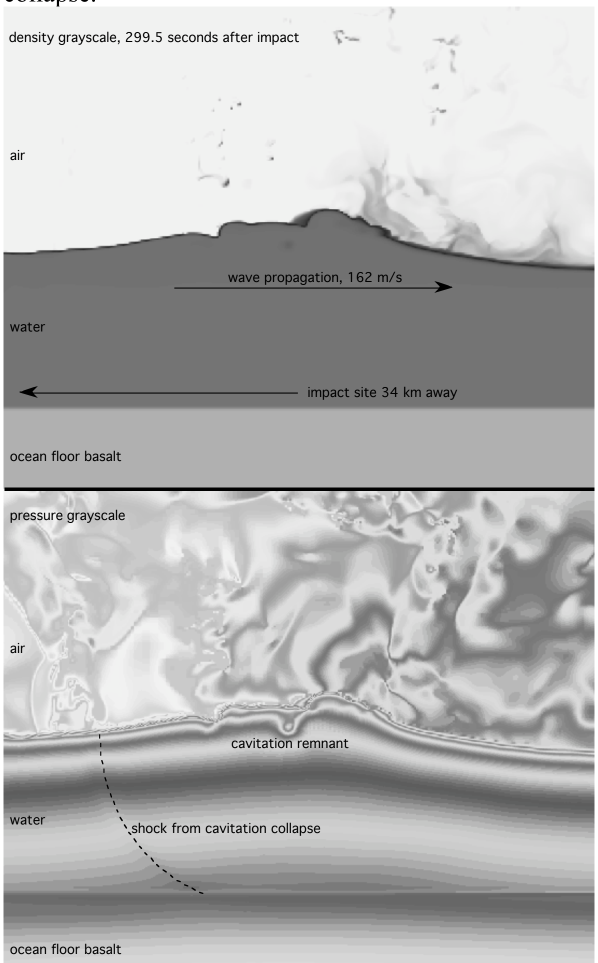

Figure 2. Plots of density (top) and pressure (bottom) in a small part of the computational volume near the crest of the leading wave in one of our simulations show evidence of continuing energy dissipation long after the impact event.

Both the extraction of wave energy by the atmosphere and the continuous generation of turbulence and cavitation within the water cause the waves to be highly dissipative; these waves are very far from energy-conserving. Unlike tsunamis generated by earthquakes or landslides, these waves decay rather more rapidly than the 1/r law expected for energy-conserving waves.

Moreover, the velocities and periods for these waves, plotted in Figure 3, are both rather less than those expected for the classical shallow-water waves generated by the usual sources of tsunamis. Both these considerations argue against significant ocean-wide damage associated with waves generated by small asteroids. To make this statement with more precision, let us establish a criterion for ocean-wide concern, in particular a one-meter wave amplitude at a distance of 1000 km from the impact event. With this criterion, the threshold of concern indicated by our simulations is the impact of a 1000m diameter dunite asteroid at 20 km/s. Anything smaller falls below the criterion postulated above for ocean-wide damage.

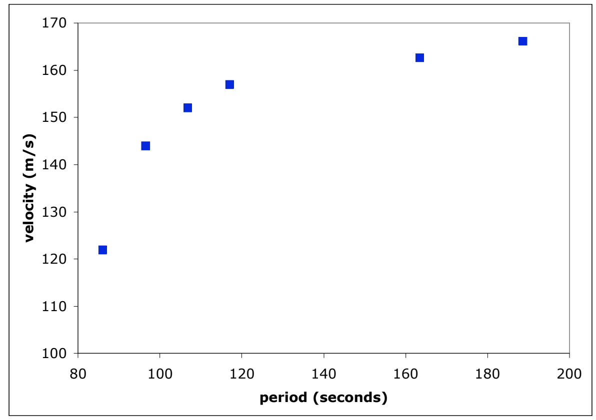

Figure 3. Velocities and periods for asteroid-induced waves are both smaller than the shallow-water values (221 km/s and ~600 seconds, in a 5-km deep ocean) expected and observed for earthquake and landslide induced tsunamis.

In fact it may even be arguable whether we are entitled to designate asteroid-impact generated waves as tsunamis, properly defined. Because of the highly dissipative and turbulent character of these waves, so different from classical tsunamis, we may need to refine our terms.

The potential for significant damage from ocean impacts of smaller asteroids must not be understated, however. The criterion adopted above (1m amplitude at 1000 km) ignores the geographical fact there are few if any parts of the earth's ocean less than 1000 km from land. Thus, while ocean-wide damage would not be expected from a 100m asteroid, for example, significant local damage will likely occur. Even for such a relatively small projectile, the input of energy to the atmosphere may be significant enough to cause disastrous (though local) firestorms.

We have also ignored ocean-floor topography in this study, and it is known that (at least for classical tsunamis) amplitudes increase dramatically as the water depth diminishes near shore. We have just begun some studies to determine if this phenomenon generalizes to impact-generated waves as well.

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