OFFSHORE BREAKING OF IMPACT TSUNAMI: VAN DORN WAS RIGHT. D. G. Korycansky, *CODEP, Department of Earth Sciences, University of California, Santa Cruz CA 95064 USA (kory@es.ucsc.edu)*, P. J. Lynett, *Coastal and Ocean Engineering Division, Department of Civil Engineering, Texas A&M University, College Station, TX 77843-3136* .

Tsunami generated by the impacts of asteroids and comets into the Earth's oceans are widely recognized as a potentially catastrophic hazard to the Earth's population (e.g. Chapman and Morrison 1994, *Nature*, **367**, 33; Hills *et al.* 1994, in *Hazards Due to Comets and Asteroids*, (ed. T. Gehrels), 779; Atkinson *et al.* 2000, *Report of the UK Task Force on Potentially Hazardous NEOs*; Ward and Asphaug 2000, *Icarus*, **145**, 64). A peculiarity of ocean impacts is the potential global effects of an impact that would otherwise be of only regional or local importance should it occur on land. This is, of course, due to the ability of waves to propagate globally, as seen by the terrible effects of the recent earthquake off the coast of Sumatra.

The overall process of an impact tsunami is complex and falls into several distinct phases: 1) initial impact of the bolide into the ocean and formation of a transient cavity in the water, 2) collapse of the cavity and propagation of large waves from the impact center outward over deep water (typically several km in depth), 3) initial effects on wave amplitude as shallower water of the continental slope is reached ("wave shoaling"), possible breaking of waves in relatively shallow water (<100 m depth) on continental shelves, and 5) final contact of waves with the shore and their progression onto dry land ("run-up" and "run-in"). Here we report on numerical calculations (and semi-analytic theory) covering phases 3 and 4.

Tsunami generated by impactors in the most hazardous size range (~ 300) m generate waves of heights (up to ~ 100 m) and periods (20–100 s) that are outside the range of normal experience due to storms or landslide and earthquake tsunami. Impacts into oceans generate a spectrum of waves with a large range in period, unlike earthquake tsunami, for which the ocean-bottom source means that only very long waves are generated. The closest analogue to impacts are waves generated by explosions, for which there is some experience, although not of energies sufficient to drive waves of the sizes studied in this paper.

For large waves, such as might be generated by large explosions or impacts, the application of breaking criteria suggests that breaking might occur far out to sea on continental shelves, and create a wide "surf zone" of large-scale turbulence extending from the shoreline all the way to the point on the shelf where the large wave first breaks. Wave breaking of large waves on continental slopes and shelves is sometimes referred as the "Van Dorn effect" (Van Dorn *et al*. 1968, *Handbook of explosion-generated water waves*; Le Méhauté 1971, *Advances in Hydroscience*, **7**, 1; Le Méhauté and Wang 1996 , *Water Waves Generated by Underwater Explosion*). According to Le Méhauté and Wang (1996) however, earlier discussions did not completely take into account the effects of wave damping by the ocean bottom leading to "exaggerated" effects (Le Méhauté and Wang 1966, p. 60). Including the damping effects gives waves that lose energy (and amplitude) fast enough to propagate inward without breaking until the last few km before the shoreline, where the bottom steepens again.

Our main tool in this effort is the wave code COULWAVE (Lynett *et al.* 2002, *Coastal Eng.*, **46**, 89). COULWAVE calculates water-wave propagation in one or two dimensions, using a nonlinear dispersive model of Boussinesq-type equations developed by several groups (Nwogu 1993, *J. Waterway Port Coast Ocean Eng.*, **119**, 618; Liu 1994, *Advances in Coastal and Ocean Engineering*, **1**, 125; Wei *et al.* 1995, *J. Fluid Mech.*, **294**, 71; Kirby 1997, *Advances in Fluid Dynamics*, **10**, 55). Such models are derived by expanding the incompressible fluid equations in powers of the parameter kh while assuming a/h is O(1), where k is the wavenumber $2\pi/L$ for a typical wavelength L, a is the typical waveheight, and h is the depth. The expansions are formally correct in the limit $kh \to 0$, but computations typically show good behavior for strongly non-linear waves $ka \sim 1$ and waves for which $kh \leq \pi$. COULWAVE solves the equations using a high-order numerical scheme (Wei *et al.* 1995) and includes a robust scheme for runup and rundown on shorelines. More details and sample validation calculations can be found in Lynett *et al.* (2002). Some details of this version of the code (that model shoreline interaction) improve upon the one presented by Lynett *et al.* (2002). In the version of the code used here, the advective terms in the equations are partially upwinded, and a numerical viscosity term is introduced into the equations. The magnitude of the numerical viscosity is given by $\nu_0(gD^3)^{1/2}$, where ν_0 is a small coefficient (10^{-4} in the calculations described below), $g = 9.81$ m s^{-2} is the gravitational acceleration, and D is the depth of the water where the waves are generated. The eddy viscosity that models wave breaking dominates the effects of numerical viscosity.

COULWAVE includes an eddy-viscosity model for wave breaking very similar to that described by Kennedy *et al.* (2000, *J. Waterway Port Coast Ocean Eng.*, **126**, 39). Wave breaking "turns on" when the time-derivative $\dot{\zeta}$ of the surface elevation is larger than a critical value $\dot{\zeta}_c = 0.65c_0$, $c_0 = [g(\zeta+h)]^{1/2}$. (Inserting $\dot{\zeta}_c$ into the linearized advection equation $\dot{\zeta} + c_0\partial\zeta/\partial x = 0$ shows that the wave breaking criterion is equivalent to a criterion on the wave slope $\partial\zeta/\partial x < -0.65$.) The coefficients of the wave-breaking model were set by matching the experimental results of Hansen and Svendsen (1979, *Regular waves in shoaling water, experimental data, Series Paper 21*, ISVA. Techn. Univ. Denmark). The numerical values were retained unchanged this study.

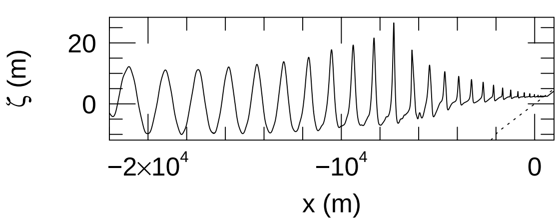
Bottom friction is modeled via a term $R_f = fu|u|/(h+\zeta)$, where u is the water velocity, $h+\zeta$ the total water depth, and f is the friction coefficient. A typical value for an ocean bed is $f = 10^{-3}$.

All calculations described here are 1D. Constant-amplitude monochromatic sinusoidal waves were generated at one side of the grid (the deep end of the bathymetry) and the waves are followed up to and past the breaking point. The code is in most cases able to handle the wave runup, but we will report on those results elsewhere in detail. For bathymetry, we used the simple piecewise linear profiles given by Le Méhauté and Wang (1996, p. 51) in particular the "Pacific coast" and "Gulf of Mexico" profiles. In order to save computational effort and perform computations in the long wave regime we started many calculations at the 100-m, 300-m, or 800-m depth mark. Some of the waves we considered have moderate increases of amplitude due to shoaling from deep water, and in most cases there was also shortening of wavelengths from their deep-water values. We took these factors into account in setting the amplitude and wavelength of the wave driver in the calculation.

In addition to the numerical calculations we investigated wave shoaling (linear and non-linear) with the aid of the calculations performed by Sakai and Battjes (1980, *Coastal Eng.*, **4**, 65). They used the high-order wave theory computations of Cokelet (1977, *Phil. Trans. R. Soc. London*, **286**, 183) to compute sequences of wave amplitudes for waves traveling into water of gradually decreasing depth. For a given value of the ratio H_0/L_0 of deep-water waveheight and wavelength, a point of maximum amplitude is reached as the depth decreases, at which point the wave breaks. Given values of H_0, L_0, and a bathymetric profile, we computed predicted offshore breaking locations x_b for comparison with the results of the numerical computations.

We performed calculations for deep-water waveheights of $H_0 = 10$, 20, 50, and 100 meters. Wave periods were $T = 20$, 40, 60, and 80 seconds, corresponding to deep-water wavelengths of $L_0 = gT^2/2\pi$ of 6.25×10^2, 2.50×10^3, 5.62×10^3, and 1.0×10^4 m.

Fig. 1



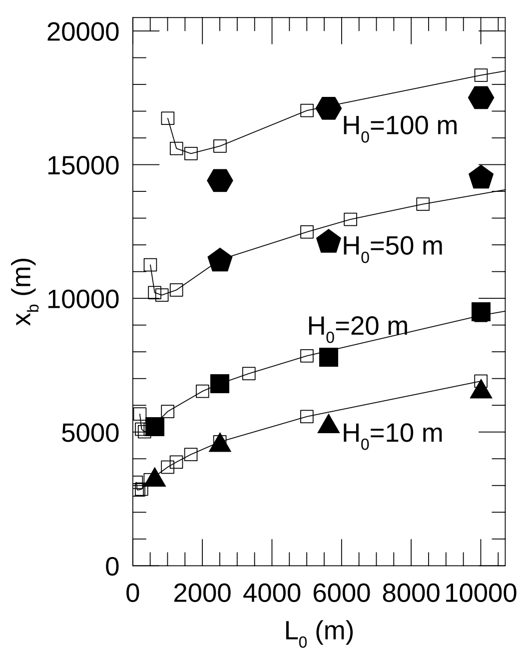
The waveheights and amplitudes cover the expected parameter space of the major parts of the wavetrains expected to be generated by the impact of a sub-km object into the deep ocean.

A typical calculation of the wavetrain $\zeta(x)$ is shown Fig. 1. Our main results are shown in Fig. 2, which shows the location of wave breaking as a function of deep-water wavelength L_0 for four different deep-water waveheights H_0, for the Pacific Coast profile. The open symbols are wave-breaking locations as predicted from calculations by Sakai and Battjes (1980). The solid symbols are computed locations of maximum offshore breaking distance from the numerical calculations. The agreement of the predictions of the two methods is very good. Waves of height $H_0 = 10$ m break $3-7$ km off shore, while 100-m waves break $15-18$ km offshore.

The results of the COULWAVE calculations shown in Fig. 2 were computed using a bottom friction parameter $f = 10^{-3}$. This fairly modest value of f is small enough that wave breaking locations are not much affected for the relatively steep Pacific coast bathymetry. Eliminating wave breaking on the Pacific coast required an increase of f to $O(10^{-1})$ in test calculations. However, calculations performed over the much gentler Gulf coast bathymetry showed no breaking with $f = 10^{-3}$. Waves were sufficiently damped by the bottom friction so as not to trigger the breaking model in the code. Eliminating bottom friction by setting $f = 0$ restored wave breaking in calculations, and the results matched the predictions obtained by using Sakai and Battjes (1980). reasonably well.

These results suggest that impact tsunami may indeed undergo a strong diminution of amplitude on continental slopes and shelves, as suggested by Melosh (2003, *34th LPSC* #2013). whether from wave breaking or bottom friction. In turn this reduces the amplitude of shoreline runup. Preliminary results from the calculations done by us suggest that the maximum transient runup is $\sim 30\%$ of the the deep-water wave amplitude, e.g. a 100-m wave will produce a maximum runup of ~ 30 m. That result was produced by an impulsively started wave; the steady-state runup from the same wave is lower yet, amounting to $\sim 10-15$ m. The maximum runup expected from a real impact is thus strongly dependent on the details of the leading part of the wavetrain. In future work we will report on a study of shoreline runup by impact tsunami wavetrains.

Fig. 2



Support for DGK was provided by NASA grant NNG04G851G "Impact Tsunami: Ocean Wave Propagation". Most of the computations were carried out on the 32-node beowulf cluster of the IGPP at UC Santa Cruz.