RUNUP FROM IMPACT TSUNAMI. 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* , S. N. Ward, *Department of Earth Sciences, University of California, Santa Cruz CA 95064 USA.*

Tsunami generated by the impacts of asteroids or comets are widely recognized as a potential hazard (Hills *et al* 1994, in *Hazards Due to Comets and Asteroids* ed. T. Gehrels, Chapman and Morrison 1994 *Nature* **367**, 33, Ward and Asphaug 2000, *Icarus*, **145**, 64, Atkinson *et al.* 2000, *Report of the UK Task Force on potentially hazardous NEOs*, Chesley and Ward 2003, *J. Geophys. Res.*, submitted). The global reach of ocean waves generated in an impact could enhance the effect of impacts whose scope would otherwise be of regional importance only. The effect is compounded by the concentration of the world's population and economic activity near ocean shorelines. It is important, therefore, to examine the potential consequences of a sizable oceanic impact.

We describe calculations we have done of the on-shore propagation of waves that might be generated from the impact of a typical small object (diameter $d = 300$ m). We are particularly interested in the maximum height on shore reached by the waves [the so-called "runup", or the maximum on-shore elevation of wave up-rush above the still-water level (Morang and Garcia 2002, *Coastal Engineering Manual*)]. We have performed a series of calculations for a relatively simple model bathymetry $h(x)$ in one spatial dimension, a depth profile typical of the Pacific coast of North America (Le Méhauté and Wang 1996, *Water Waves Generated by Underwater Explosion*). Given the large parameter space of potential impactors and impact locations, the wide diversity of shoreline bathymetry around the world, and the potential for strong refraction due to local depth variations, we do not attempt an exhaustive characterization.

The calculations were done with the COULWAVE code (Lynett *et al.* 2002, *Coastal Eng.*, **46**, 89), that models the propagation and shore-interaction of non-linear moderate- to long-wavelength waves (wavenumber $kh < \pi$) using the extended Boussinesq approximation to the full Navier-Stokes equations (cf. Liu 1994, *Advances in Coastal and Ocean Engineering*, **1**, 125, Kirby 1997, *Advances in Fluid Dynamics*, **10**, 50). COULWAVE models wave propagation over variable bathymetry including wave runup onto dry shorelines, bottom friction, and a time- and space-dependent dissipation that models the energy loss suffered by breaking waves (Kennedy *et al.* 2000, *J. Waterway Port Coast Ocean Eng.*, **126**, 39). Previous work of ours (Korycansky and Lynett 2005 *Geophys. Rev. Lett.*, **32**, L10805) is consistent with the existence of the so-called "Van Dorn effect" (Van Dorn *et al.* 1968, *Handbook of explosion-generated water waves*), in which large (10-100 m height) waves with periods $T = 20-80$ sec, typical of those generated by impacts, break at distances up to ~ 15 km off-shore (for Pacific coast bathymetry), due to non-linear shoaling.

We first validated the code by comparison of its results with laboratory wave tank experimental measurements of the runup

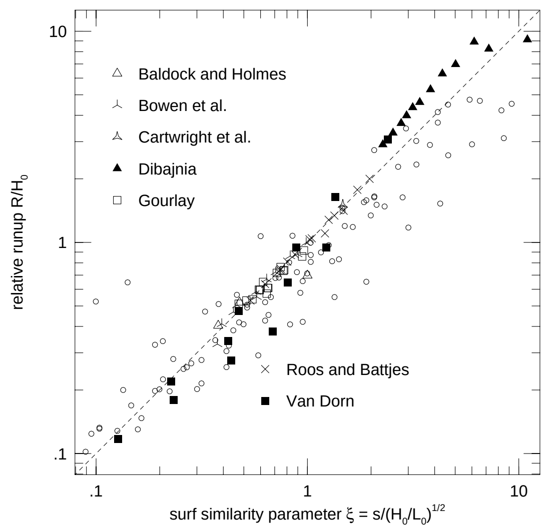

Figure 1: Wave tank experimental measurements of runup from the literature (labeled points) and COULWAVE runup results (open circles).

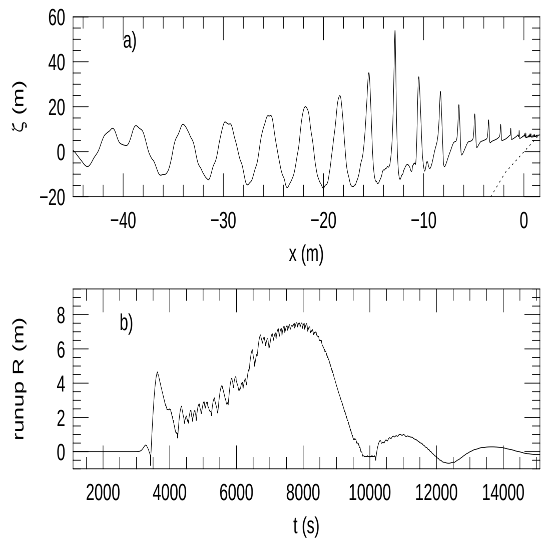

Figure 2: a) Waveheight ζ as a function of distance x for $t = 8100$ s for the case in which the impact is 400 km distant from the 800-m depth mark on the grid. b) Runup R as a function of time for the wave trains generated by the impact of a 300-m diameter object into deep water, for the impactor at 400 km distance.

R of monochromatic waves of "deep-water" (un-shoaled) waveheight H_0 and deep-water wavelength $L_0 = gT^2/2\pi$ onto model beaches with slopes s. Both experimental and COULWAVE results are reasonably well-described by the formula $R/H_0 = \xi$, where ξ is the surf-similarity parameter (Irribaren number) given by $\xi = s(H_0/L_0)^{1/2}$ (Battjes 1974, *Proc. 14th Coastal Eng. Conf.*, 466), as seen in Fig. 1. (Experimental results in Fig. 1 are given by Bowen *et al.* 1968 *J. Geophys Res.* **73**, 2569, Roos and Battjes 1976, *Proc. 15th Coastal Eng. Conf.*, 781, Van Dorn 1976, *Proc. 15th Coastal Eng. Conf.*, 738, Van Dorn 1978, *J. Geophys. Res.* **83**, 2981, Gourlay 1992, *Coastal Eng.*, **17**, 93, Baldock and Holmes 1999 *Coastal. Eng.* **36**, 219, Cartwright*et al.* 2002 *Proc. 28th Coastal Eng. Conf.*, 1006, and Dijabnia 2002, *Proc. 28th Coastal Eng. Conf.*, 955. COULWAVE calculations were performed using parameters chosen from the following sets: $s = [0.01, 0.02, 0.05, 0.1, 0.2]$, $L = [2, 5, 10, 20]$ m, and $H = [0.01, 0.02, 0.05, 0.1, 0.2]$ m.)

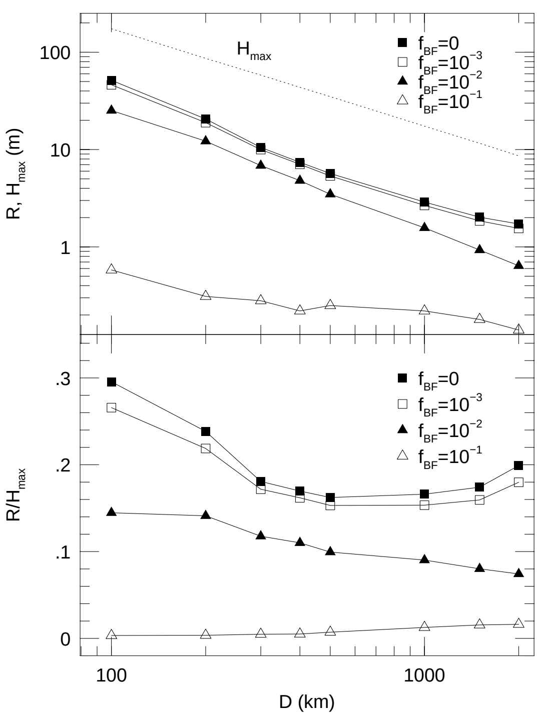

Figure 3: Runup R (and maximum waveheight H_{max}) as a function of distance D from the impact site to the 800-m depth mark. Top panel: R vs. D for values of bottom friction $f_{BF} = 0$, 10^{-3}, 10^{-2}, and 10^{-1}. Also shown is H_{max}. Bottom panel: the ratio R/H_{max} vs. D for the same values of bottom friction.

Following the comparison with laboratory results, we calculated runup from impact-generated waves on the above-mentioned Pacific coast profile. For impact runup calculations, input wave trains were generated from the collapse of a parabolic transient cavity of dimensions appropriate to the impact of 300-m diameter asteroid into deep water (Ward and Asphaug 2000). The calculations were started from the 800-m depth mark, 40 km from the shoreline. We calculations for various amounts of bottom friction coefficient $f_{BF} = 0\ 10^{-3}$, 10^{-2}, and 10^{-1}. The wave profile ζ as a function of off-shore distance x is shown in Fig. 2 at a particular instant of time $t = 8100$ s for the case in which the impact is 400 km distant from the 800-m depth mark on the grid. The near-shore mean water depth is elevated, a phenomenon known as "wave set-up". Fig. 2 also shows the runup as a function of time. Note that the runup remains substantial for a significant period of time, several hours in this case, due to wave set-up. Depending on the local on-shore topography, waves could therefore propagate inland for quite substantial distances.

We calculated the runup R for a number of off-shore impact distances D from 100 to 2000 km. For $D = 100$ km, we found $R \approx 0.3H_{max}$, where H_{max} is the maximum waveheight of the tsunami wave train. The ratio R/H_{max} decreases somewhat for larger distances; for $D > 300$ km, $R \sim 0.17H_{max}$ for a low-friction ocean floor. The runup R is shown as a function of D in Fig. 3.

Taken at face value, these results suggest that wave breaking and associated energy loss is fairly effective at reducing the amplitude from waves generated by impact tsunami. On the other hand, wave set-up noted above could enhance the expected hazard. However, a number of questions remain as to the validity of the calculations we have performed. For example, it will be noted that R/H_{max} as seen in Fig. 3 is roughly constant for maximum waveheights that range over a factor of ~ 20 as a function of distance from the impact point. This contrasts with the laboratory-scale behavior, which would predict that R/H_{max} would scale as $H_{max}^{-1/2}$; that is, relative runup would actually increase with distance from the impact center (although absolute runup R would decrease roughly $\sim D^{-1/2}$, as linear theory predicts that the wave train amplitude H_{max} decreases as D^{-1}). The reason for this difference in behavior is not clear. Possible causes may involve 1) the compound slope of the bathymetric profile, 2) a difference between monochromatic wave runup and that produced by a wave train with time-varying amplitude and frequency, 3) a failure of the dissipation model incorporated into COULWAVE to account properly the breaking for large-amplitude long waves, or 4) excess numerical dissipation in COULWAVE. Additionally, similarity scaling for R could lose validity for the small values of ξ that apply for impact tsunami and which are outside the experimental range shown in Fig. 1. Further testing of COULWAVE's behavior is being carried out to address these questions.

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