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Nonlinear wave runup in long bays and firths: Samoa 2009 and Tohoku 2011 tsunamis

I. Didenkulova (1,2) and E. Pelinovsky (3)

(1) Institute of Cybernetics, Laboratory of Wave Engineering, Tallinn, Estonia (ira@cs.ioc.ee, +372 6204151), (2) Nizhny Novgorod State Technical University, Nizhny Novgorod, Russia, (3) Institute of Applied Physics, Department of Nonlinear Geophysical Processes, Nizhny Novgorod, Russia

Last catastrophic tsunami events in Samoa on 29 September 2009 and in Japan on 11 March 2011 demonstrated that tsunami may experience abnormal amplification in long bays and firths and result in an unexpectedly high wave runup. The capital city Pago Pago, which is located at the toe of a narrow 4-km-long bay and represents the most characteristic example of a long and narrow bay, was considerably damaged during Samoa 2009 tsunami (destroyed infrastructures, boats and shipping containers carried inland into commercial areas, etc.) The runup height there reached 8 m over an inundation of 538 m at its toe, while the tsunami wave height measured by the tide-gauge at the entrance of the bay was at most 3 m. The same situation was observed during catastrophic Tohoku tsunami in Japan, which coast contains numerous long bays and firths, which experienced the highest wave runup and the strongest amplification. Such examples are villages: Ofunato, Ryori Bay, where the wave runup reached 30 m high, and Onagawa, where the wave amplified up to 17 m.

Here we study the nonlinear dynamics of tsunami waves in an inclined U-shaped bay. Nonlinear shallow water equations can in this case be written in 1D form and solved analytically with the use of the hodograph transformation. This approach generalizes the well-known Carrier-Greenspan transformation for long wave runup on a plane beach. In the case of an inclined U-shaped bay it leads to the associated generalized wave equation for symmetrical wave in fractal space. In the special case of the channel of parabolic cross-section it is a spherical symmetrical linear wave equation. As a result, the solution of the Cauchy problem can be expressed in terms of elementary functions and has a simple form (with respect to analysis) for any kind of initial conditions.

Wave regimes associated with various localized initial conditions, corresponding to problems of evolution and runup of tsunami, are considered and analyzed. Special attention is paid to the wave breaking criterion.

Theoretical estimates of tsunami runup are applied to cases of 2009 Samoa and 2011 Tohoku tsunamis. The data of tide-gauges or computed tide-gauges are used to calculate wave runup for two approximations of the bottom topography: a plane beach and for a narrow bay. It is shown that theory of 1D runup on a plane beach underestimate the tsunami runup height and the influence of the narrow bay geometry should be taken into account. The differences in estimated shoreline velocity, travel time and wave breaking regime, calculated in the framework of these two approximations are also discussed. It is concluded that the wave runup in narrow bays should by calculated by the corresponding formulas, which should be taken into account by TEWS.