MECHANISMS OF TSUNAMI GENERATION BY IMPACTS. V.V. Shuvalov, Institute for Dynamics of Geospheres RAS, Leninsky pr. 38-1, 119334 Moscow, Russia, e-mail: shuvalov@idg.chph.ras.ru.

Introduction. At present, tsunami waves are considered as one of the main shock factors in the problem of asteroid hazards [1]. In the analysis of the consequences of tsunami arising on the marine impact of cosmic bodies, the following formula is commonly used [2]

$$h = 45\frac{H}{L}(Y)^{0.25},$$

where H is the water basin depth, h is the wave amplitude in meters, L is the distance from the source, and Y is the released energy in kitotons TNT equivalent. This formula was derived from the analysis of data obtained at the Baker nuclear explosion in the 60-m deep lagoon on Bikini atoll; its energy was about 20 kt [2].

However, the existing results of experimental and theoretical studies show that the cratering process in marine targets and a mechanism of tsunami formation strongly depends on the parameter d/H, where d is the impactor diameter and H is the sea depth. When $d/H < 0.1$, no underwater crater is formed at all [3], and tsunami wave results from the collapse of water transient cavity. When $d > H$, the water column has almost no effect on the crater-forming flow [4] and tsunami wave is formed due to the expulsion of water by the rim of the crater that grows in the soil and by the uplift of the sea floor in the cratering flow process. The most complicated flow arises in the intermediate case when $0.1 < d/H < 1$.

Recently Melosh [5] has concluted that tsunami created by asteroids < 1 km in diameter could not cause strong devastation to coastal areas. His conclusions are based on the report of the US Office of Naval Research [6] summarising the results obtained for tsunami generated by nuclear explosions in the ocean. According to this report waves with periods in the range of 20 to 100 s are axpected to break on the outer continental shelf and tsunami with litlle onshore damage (contrary to tsunami with periods of 100 s to 1 hour generated by earth quakes). This means that in order to estimate a risk from impact generated tsunami we should also calculate a period of these waves.

In this study I analyze these three regimes of underwater crater formation and tsunami generation by means of numerical modelling of the three terrestrial marine target impacts: Eltanin, Lockne, and Mjølnir. These impact structures are well studied and characterize the typical regimes of crater formation at different ratios of impactor diameter to the sea depth: d/H =0.25 for Eltanin, d/H =4 for Mjølnir, and d/H =1 for Lockne.

Numerical model. The SOVA multi-dimensional multi-material hydrocode [7] is used to simulate main stages of the impact (the impactor penetration into the target, the crater-forming flow, the filling of the crater with water, the generation of tsunami waves).

To calculate the thermodynamic parameters of air, water, and soil the tabular equation of state for air [8], the Tillotson equation of state [9], and the tables obtained by the ANEOS code [10] are employed.

The model of strength developed by Melosh and Ivanov [11] and the algorithm for taking "acoustic fluidization" into account were included into the SOVA code in order to simulate the crater modification.

Eltanin. Eltanin [12] is the only presently known impact structure formed during the fall of a cosmic body into a deep (4–5 km) oceanic basin. According to the estimates made by Gersonde and Kyte [13], the impact structure of Eltanin was formed on impact of an asteroid 0.5–2 km in size that occurred 2.2 Myr ago. No traces of the underwater crater have been discovered.

Numerical simulations of a vertical impact of a 1-km-diameter asteroid show that approximately at 30 s after the impact a transient water cavity 15 km in diameter is formed. Its collapse produces tsunami waves with amplitudes 1200, 800, 450, and 320 m at distances 20, 30, 50, and 70 km from the impact point. Formula (1) gives the wave amlitudes 850, 570, 340, and 240 m at the same distances. Since the difference does not exceed 30% the agreement can be considered as satisfactory. A period of the tsunami waves is about 150 s. This correlates well with

Mjølnir. According to Dypvik et al. [14], the 40-km-diameter Mjølnir crater in the Barents Sea is a result of the impact of an asteroid that occurred 140 Myr ago. The estimated diameter of the asteroid is 1-3 km; the probable depth of the sea was 300--500 m. In this case the water layer is very thin in comparison with crater depth, it very slightly influences the cratering flow. The rim of the growing crater pushes the sea water outward and upward, thereby generating a water surge. This surge moves from the center ahead of the crater wall and the excavated-material cone. The height of the water surge increases first, and then the surge collapses, breaking down into several waves. The interaction between these waves results in a tsunami.

For the energy 250 Gtons of TNT equivalent released at the formation of the Mjølnir crater, the formula of Glasstone and Dolan gives an amplitude of about 40 m at a distance of about 60 km from the crater center. This value is significantly lower than that obtained in our simulations (about 200 m). The reason of this discrepancy is another mechanism of tsunami generation. Both in the Eltanin and Bikini test tsunami wave was a result of transient water crater evolution and collapse. In the Mjølnir case tsunami is generated by the motion of solid material. In some sence it is more similar to landslides induced tsunami when the wave is generated due to motion of solid surfaces. As a result we have another energy-amplitude dependence. We also have a much large period of the waves – about 1000 s.

Lockne. The age of the underwater crater Lockne located in Sweden is estimated to be approximately 450 Myr [15]. Presumably, this crater is the result of the fall of an asteroid into the sea with a depth ranging from 200 to 1000 m. More exect estimate is 500–700 m [16]. Numerical simulations for depthes 200, 500, and 1000 m show a gradual transition from a Mjølnir-like to an Eltanin-like mechanism of tsunami generation. Modification of basement crater and its infilling by water makes the flow much more complicated. In both last cases (Lockne and Mjolnir) similar to earthquake generated tsunami a net volume of water (negative) is transported across a large area of the ocean. The net volume appears due to formation of basemend crater. This effect increases a period of the wave.

Asymmetry of tsunami waves produced by oblique impacts. The process of cratering can roughly be divided into three stages: compression/penetration, excavation, and modification [17]. In the case of oblique impacts the penetration is strongly asymmetrical, occurring at distances comparable to projectile size. The modification stage, in contrast, is close to symmetrical because the size of the final crater (i.e., characteristic size of modification process) is considerably larger than the projectile size, and initial asymmetry attenuates at high distance. It is comparable to a high energy explosion, where shock wave propagation and cratering depend on the energy release only. The excavation is an intermediate stage with early ejecta being strongly asymmetrical and late ejecta (forming crater rim) only slightly asymmetrical.

Therefore we can expect that all effects produced during the penetration and early excavation stage should be asymmetric (for example distal ejecta) and all phenomena generated during the modification stage should be near symmetric (all craters are near circular). Tsunami waves form during the late modification stage and we should not expect strong asymmetry. Of course, this concerns only moderately oblique impacts (with angles exceeding 20-30 degrees to horizon). Grazing impacts can probably produce strongly asymmetric waves. Numerical simulations confirm this conclusion.

Conclusions. There are two mechanisms of tsunami-wave generation by marine target impacts: If the sea depth exceeds the impactor diameter by a factor of 2-4 or more, tsunamis are generated at the infilling of the transient water crater, and the wave amplitude can be estimated using the formulas derived for underwater nuclear explosions. If the impactor size is larger than the sea depth, tsunamis are formed due to the expulsion of water by the rim of the crater that grows in the soil and by the uplift of the sea floor in the cratering flow process. In this case, the wave amplitude and period can be several times larger than that estimated by the formulas for nuclear explosions.

And in the intermediate case we have even more complicated mechanism of tsunami formation. And one more conclusion: a use of any simplified formulas for the initial shape velocity distributions can lead to strong errors in determination of tsunami energy and amplitude.

Oblique impacts produce almost symmetrical tsunami wave.

References: [1] Adushkin V.V. and Nemchinov I.V. (1994) *Hazards due to Comets and Asteroids* (Ed. T.Gehrels), 721-778. [2] Glasstone S. and Dolan P.J. (1977) *The effects of nuclear weapons,* 653 p. [3] Gault D.E. and Ch.P. Sonett (1982) *GSA Special Paper, 190*, 69-92. [4] Shuvalov V. et al. (2002) *JGR,* 10.1029/2001JE001698, 1-1–1-12. [5] Melosh H.J. (2003) LPSC XXXIV, #2013. [6] Van Dorn et al. (1968) *Handbook of explosion-generated water waves.* [7] Shuvalov V.V. (1999) *Shock Waves, 9*(6), 381-390. [8] Kuznetsov N.M. (1965) *Thermodynamic Functions and Shock Adiabats for air at High Temperatures*, 464 p., (in Russian) [9] Tillotson J.H. (1962) *General Atomic Rep. GA-3216*, 137p. [10] Thompson S.L. and Lauson H.S. (1972) *Rep. SC-RR-71 0714*, 119 pp., Sandia National Lab. [11] Melosh H.J. and Ivanov B.A. (1999) *Annu. Rev. Earth Planet. Sci., 27*, 385–425. [12] Gersonde R. et al. (1997) *Nature, 390*, 357-363. [13] Gersonde R. and Kyte F. T. (2001) *Meteoritics & Planet. Sci.*, 36, Supplement, p.A64. [14] Dypvik H. et al. (1996) *Geology, 24*, 779–782. [15] Ormö J. and Lindström M. (2000) *Geol. Mag., 137*(1), 67–80. [16] Ormö J. et al. (2002) *JGR, 107*, 3-1–3-9. [17] Melosh H.J. (1989) *Impact Cratering: A Geologic Process*, 245 pp.