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C. R. Physique 6 (2005) 361–366
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The Near Earth Objects: possible impactors of the Earth/Les astéroïdes geocroiseurs : impacteurs potentiels de la Terre

Asteroid impact tsunamis

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Available online 17 February 2005

Presented by Pierre Encrenaz

Abstract

A review of the known historic asteroid impacts generating huge tsunamis at the sea surface is provided. Different approaches from the linear theories to Navier–Stokes equations and hydrocode models are very briefly presented or referenced. The propagation and run-up stage of tsunamis is discussed and the important role of the sea bottom topography is emphasized. Further studies focusing on propagation and run-up are suggested to extend previous works on the subject. ***To cite this article: C. Kharif, E. Pelinovsky, C. R. Physique 6 (2005).***

Résumé

Tsunamis dus à l'impact d'astéroïdes. Une revue des impacts d'astéroïdes survenus dans le passé et ayant généré d'énormes tsunamis à la surface de l'océan est présentée. Différentes approches depuis les théories linéaires aux équations de Navier–Stokes et aux modèles de type hydrocode sont présentées succinctement ou citées en références. La propagation de tsunamis et leur 'run-up' sont discutés et le rôle majeur tenu par la bathymétrie est mis en avant. Des études futures sur la propagation et le 'run-up' sont proposées afin d'étendre les travaux antérieurs sur le sujet. ***Pour citer cet article : C. Kharif, E. Pelinovsky, C. R. Physique 6 (2005).***

Keywords: Tsunamis; Asteroid impacts

Mots-clés : Tsunamis ; Impacts d'astéroïdes

1. History of tsunami impact

Possible impact of asteroids in the ocean may induce the formation of giant sea waves called tsunami. Usually, tsunami waves are generated by underwater earthquakes, underwater volcanoes, rocks and landslides, and so on [1–3]. Some historic events have been recorded worldwide, in particular, the eruption of the Krakatau volcano (Indonesia) in 1883 generated sea waves in Indian, Atlantic and Pacific oceans [4,5]. The total energy released by this volcano eruption was equivalent to 200 megaton atomic bombs (8.4×10^{17} joules). The amount of energy released by the asteroid impact can be much larger. Asteroids larger than 200 meters in diameter hit Earth about every 3000–5000 years, so the probability of one impacting in a given human

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1631-0705/$ – see front matter
doi:10.1016/j.crhy.2004.12.016

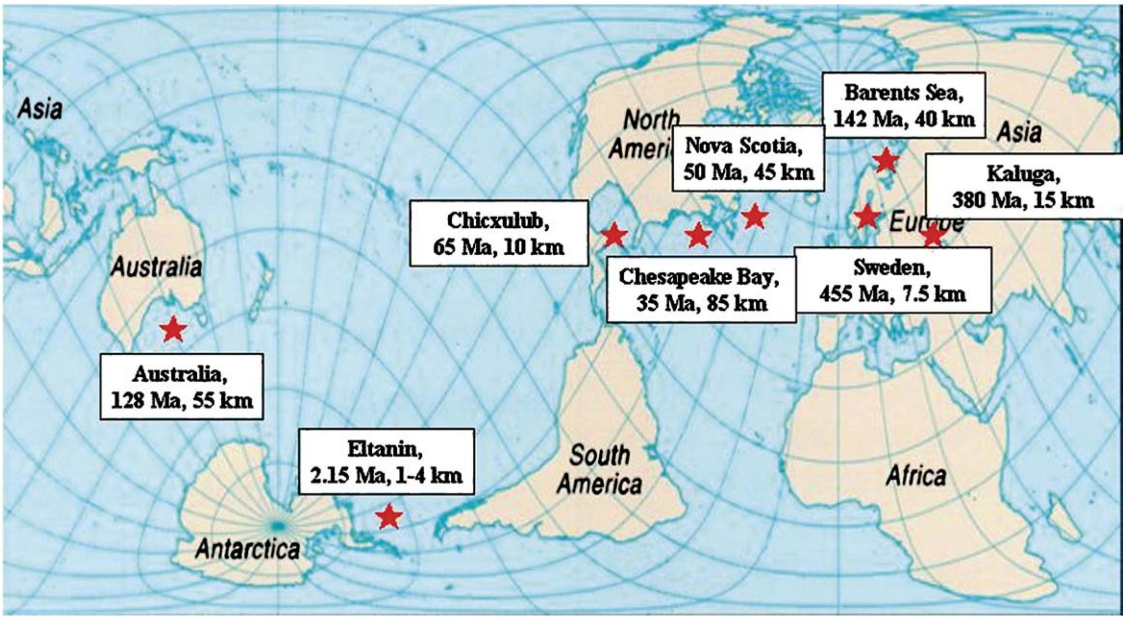

Fig. 1. Map of known asteroid entries into the sea.

lifetime is about 2–3% [6]. The evidence of oceanic impact of asteroids is growing now with the use of methods of marine geology [7]. Perhaps, the first was the 455 Ma old marine-target Lockne impact crater (Sweden) [8]. The water depth in this site was at least 200 m, and the inner crater diameter is 7.5 km. The second was the Kaluga (Russia) impact event that occurred about 380 Ma ago in the marine environment (epicontinental sea) with a water depth of at least 300 m; the crater diameter is about 15 km [9]. The generated seismic shock and tsunami have produced geological features as far as 500 km away from the impact site. The 40 km-diameter Mjølnir crater in the Barents Sea was created by an asteroid impact into a 400 m shallow sea about 142 Ma ago [10]. Tsunami deposits confirmed another event that occurred 65 million years ago, when an asteroid with a diameter of about 10 km struck the shallow sea near Chicxulub, Mexico [11–13]. The entry of the 'Eltanin' asteroid with diameter about 1–4 km into the Bellingshausen Sea (SE Pacific) of depth 5 km during the late Pliocene (2.15 Ma) is now well documented [7,13–16]. Some other events that occurred in Australia, USA (Virginia) and Canada (Nova Scotia) are also mentioned [7]. The geographical distribution of the known asteroid entries into the sea is shown in Fig. 1. The collision of the asteroid 1950 DA (29075) with the Earth on 16 March 2880, is predicted with probability of 0.33% [17]. Taking into account the catastrophic consequences of asteroid collisions with the Earth, several special workshops have been organized [7,18].

2. Modeling tsunami impact

The initial stage of tsunami generated by asteroid impacts is a very tricky task, and various computed scenarios of water disturbances due to an asteroid impacting the water are described in [10,19–24]. All of these models predict large values (comparable with the water depth) of water disturbances in the source and a characteristic length scale (source radius) comparable to the asteroid diameter. Such calculations require large computer resources, and usually the numerical codes developed for the initial stage are matched with known numerical models of tsunami propagation.

The first approach uses the shallow-water theory usually applied for tsunamis induced by underwater earthquakes. In spherical coordinates the basic equations including the Earth rotation are,

$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\theta}\left\{\frac{\partial M}{\partial \varphi} + \frac{\partial}{\partial \theta}(N\cos\theta)\right\} = 0, \tag{1}$$

$$\frac{\partial M}{\partial t} + \frac{gh}{R\cos\theta}\frac{\partial \eta}{\partial \varphi} = fN, \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{gh}{R\cos\theta}\frac{\partial \eta}{\partial \theta} = -fM, \tag{3}$$

where $M(\theta,\varphi,t)$ and $N(\theta,\varphi,t)$ are the flow discharges in meridional and zonal directions, $\eta(\theta,\varphi,t)$ is the water displacement and f is the Coriolis parameter. For coastal zone the nonlinearity and bottom friction are important and here Cartesian coordinates and nonlinear shallow-water equations with moving boundary

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0, \tag{4}$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{k}{2D^2}M\sqrt{M^2+N^2}=0, \tag{5}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\frac{k}{2D^2}N\sqrt{M^2+N^2}=0 \tag{6}$$

can be used. Here $D=h+\eta$ is the total water depth and k is the friction coefficient (usually $k=0.0025$). Numerical schemes and matching of various systems of equations for tsunami waves are discussed in [25]. Numerical simulations in the framework of shallow water equations were performed in [8,26,27]. Noting that the characteristic scale of water displacement in the source may be comparable with the water depth, dispersive effects should be important. In fact, this is pointed out in [19], who compared the results of simulation in the framework of the nonlinear shallow-water equations and incompressible Navier–Stokes equations. The tsunami wave amplitudes and velocities within the exact model are smaller than the shallow-water wave values.

Due to the complex character of the processes in the tsunami source and the possibility of using classical hydrodynamic models of tsunami propagation, the tsunami source shall be parametrized. The design of the equivalent tsunami source of a parabolic cavity (water displacement in the source)

$$\eta(r,0)=D_c\left(1-\frac{r^2}{R_c^2}\right), \tag{7}$$

(D_c and R_c are effective depth and radius of the cavity) has been applied for many years to describe the waves generated by explosions in water [28] and explosive eruptions of underwater volcanoes [29]. The same ideas have been developed for asteroids striking the ocean by Ward and Asphaug [13]. It is assumed that only a fraction, ε, of the kinetic energy of the impactor goes into making the tsunami. Hence the depth of the cavity is given by

$$D_c=\sqrt{\frac{2\varepsilon\rho_i R_i^3 V_i^2}{\rho_w g R_c^2}}, \tag{8}$$

where ρ_i, R_i and V_i are the density, radius and velocity of the impactor respectively and ρ_w is the water density. Ward and Asphaug [13] suggested a general relationship between the depth and radius of the cavity of the form $D_c=qR_c^{\alpha}$, where the parameters q and α depend on the properties of the impactor. Substituting this relation into Eq. (8) gives the diameter of the cavity

$$d_c=2R_i\left(\frac{2\varepsilon V_i^2}{gR_i}\right)^{\delta}\left(\frac{\rho_i}{\rho_w}\right)^{\delta}\left(\frac{1}{qR_i^{\alpha-1}}\right)^{2\delta} \tag{9}$$

with $\delta=1/2(1+\alpha)$. From laboratory impact experiments in water $\alpha=1.27$. Fig. 2 displays cavity diameter and cavity depth as a function of the asteroid radius for $V_i=20$ km/s, $\rho_i=3$ g/cm^3, (corresponding to $q=0.1$). In the average the ratio of the cavity diameter to the cavity depth is 2.5–3.

For sources with radius comparable to water depth the dispersion effects become important. Due to wave dispersion, the wave height is attenuated and far from the source the wave can be considered as linear. The linear theory of water waves is well developed and the main conclusions can be given before any calculations. If the cavity radius is smaller than water depth, deep-water approximation can be applied. In this case, the water elevation at the surface position $\boldsymbol{r}$ and time t is expressed in terms of an integral of the following form

$$\eta(\boldsymbol{r},t)=\mathrm{Re}\left\{\frac{1}{4\pi^2}\int_k\left(\eta_0(\boldsymbol{r}_0)\,\mathrm{e}^{-\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}_0}\,\mathrm{d}\boldsymbol{r}_0\right)\mathrm{e}^{\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{r}-\omega(k)t)}\,\mathrm{d}\boldsymbol{k}\right\} \tag{10}$$

With $k=|\boldsymbol{k}|$, $\boldsymbol{r}_0=\boldsymbol{r}(t=0)$ and $\eta(\boldsymbol{r}_0)=\eta(r,0)$. $\mathrm{Re}\{\cdot\}$ means the real part and $\boldsymbol{k}$ is the wavevector. The frequency ω is given by the linear dispersion relation of gravity waves propagating in finite depth

$$\omega(k)=\sqrt{gk\tanh kh}, \tag{11}$$

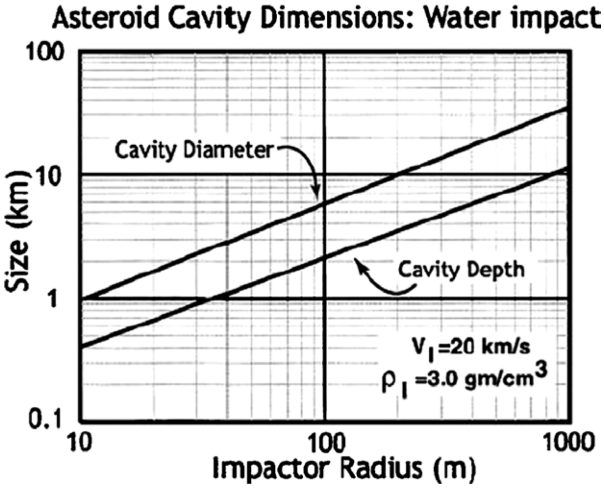

Fig. 2. Characteristics of the equivalent tsunami source [13].

where g and h are the gravitational acceleration and ocean depth respectively. The optimal wave train is obtained when all of the water deposits into the bordering lip of the cavity due to asteriod impact. In this case $R_D = (2)^{1/2} R_c$, where R_D and R_c are the inner and outer radii of the cavity. The initial shape is given by Eq. (7) for $r \leqslant R_D$ and $\eta(\boldsymbol{r}, 0) = 0$ for $r > R_D$. Due to the cylindrical symmetry Eq. (10) becomes

$$\eta(\boldsymbol{r}, t) = \frac{1}{2\pi} \int_0^\infty k f(k, R_C, R_D) J_0(kr) \cos\bigl(\omega(k)t\bigr)\, \mathrm{d}k \tag{12}$$

with

$$f(k, R_C, R_D) = \frac{4\pi D_C}{k^2} \left(\frac{R_D}{R_C}\right)^2 \bigl(J_2(kR_D) - k(R_D^2 - R_C^2) J_1(kR_D)/2R_D\bigr),$$

where D_c denotes the initial cavity depth and $J_n(\cdot)$ the cylindrical Bessel functions. The maximum tsunami height occurs near to the peak of the spectrum,

$$k_m = \frac{2\pi}{2.11 R_c}. \tag{13}$$

The wavelength at peak tsunami height is close to the diameter of the cavity. Moreover, for large distances from the source using the stationary phase approximation it is easy to show that the maximum wave amplitude decreases with distance as r^{-1} [30]. Using the linear theory of water waves with the equivalent source described above and knowing probabilities of asteroid collisions with the Earth, Ward and Asphaug [13] developed the probabilistic hazard assessment of the asteroid impact tsunami. It is important to mention that this simplified approach may be used for relatively weak events, when the asteroid diameter is less than 1 km. Meanwhile, as it can be shown [2], the amplitude of the leading wave, initially weak, decreases slowly (as $r^{-5/6}$ in water of constant depth) and this wave can prevail on large distance; bottom inhomogeneities modifies its amplitude, sometimes leading to wave amplification. This important question requires a particular attention.

When the tsunami wave approaches to the coast, it becomes nonlinear and this process can be described in the framework of the nonlinear theory of wave run-up and here some analytic formulas can be derived for simple geometries of coastal zone (plane beach) [31–34]. The result depends from the wave shape. Ward and Asphaug [35] assume that the approximate wave has a soliton-like shape and give some estimates of the wave run-up, but this assumption is not justified because the wave packet in the open sea is a quasi-sinusoidal group. Run-up of the sine wave is described by [32]

$$\frac{R}{H_0} = \sqrt{\pi\omega\sqrt{L/g}}(\cot\beta)^{1/4}, \tag{14}$$

where H_0 is the height of the incident wave of frequency ω, L is the distance from the coast, $\tan(\beta)$ is a beach slope, and R is the maximum run-up height. In fact, the detail of the relief bottom and land topography plays a very important role and here accurate numerical two-dimensional models should be applied to obtain tsunami height distribution along the coast [25].

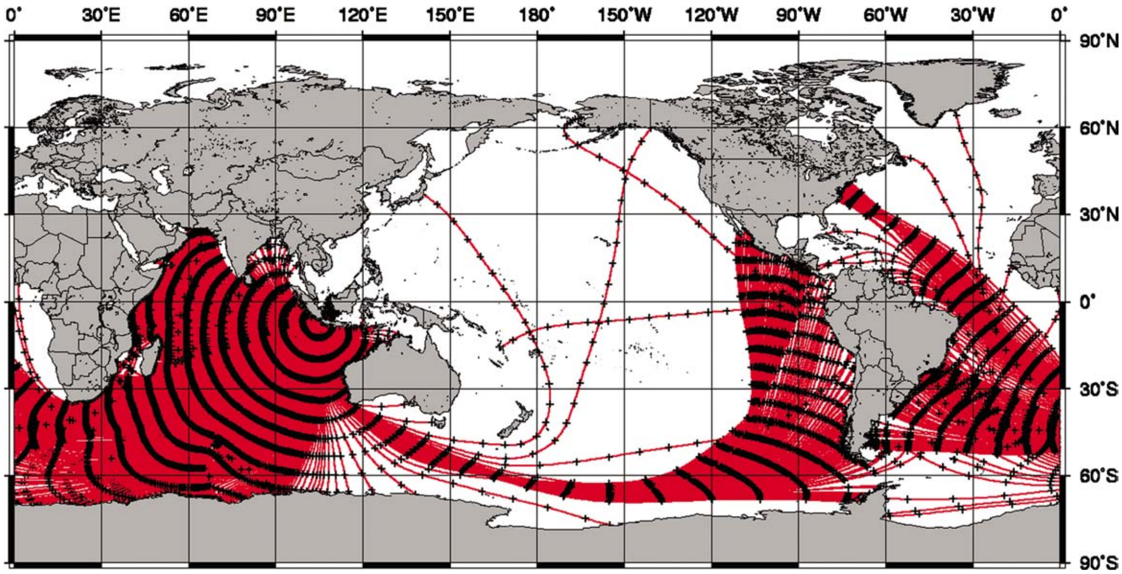

Fig. 3. Global propagation of the 1883 Krakatau volcano tsunami [5].

The approach described above has been applied to estimate the tsunami induced by the Eltanin asteroid [14]. Assuming the asteroid diameter is 4 km, they found an initial cavity as deep as the ocean and 60 km wide. Tsunami waves may reach 200–300 m high in the Antarctic Peninsula and 60 m in New Zealand. The same approach was used recently to forecast the possible collision of a 1.1 km diameter asteroid (1950 DA) with the Earth in 2880 [35]. Traveling at 17.8 km/s the asteroid may strike the ocean 600 km east of the United States coast and would blow a cavity 19 km in diameter. The use of the linear theory for a fluid of constant depth together with shoaling and run-up corrections allows the prediction of tsunami heights along the coast. Waves would strike the coast of Europe and Africa within 12 hours and their height would reach 23 m in Ireland, 16 m in England, 17–21 m in France, and 15 m in Portugal. In fact, in both papers, the detailed relief of the seafloor was not considered (effects of refraction and diffraction), and these calculations may under- or over-estimate the values of tsunami heights. Very accurate simulations of the global tsunami propagation using ETOPE2 dataset have been made recently by Choi et al. [5] for the catastrophic 1883 Krakatau volcano eruption (Fig. 3). They demonstrate the strong influence of the bottom relief on tsunami propagation; in fact, tsunami from the Indian ocean does not penetrate in the Pacific ocean.

3. Conclusions

This brief review shows that tsunami induced by the asteroid impact differ from tsunami generated by underwater earthquakes and require modifications of the existing theories of tsunami waves at all stages of tsunami generation, propagation and run-up. In our opinion, perspectives for asteroid tsunami investigations should concern the following tasks:

- 2D and 3D numerical simulations of the initial stage of the tsunami generation in the framework of the fully nonlinear potential theory or Navier–Stokes equation, at least on a domain of size 5–10 asteroid diameters and matching with the code based on the linear dispersive theory; it is required to formulate the equivalent 'asteroid tsunami' source for all possible regimes of the asteroid entry into the sea;
- incorporation the depth variation in the open sea in the numerical code of the linear dispersive theory;
- nonlinear simulations of tsunami waves propagation near the coasts by using shallow-water codes (for instance, international code TUNAMI here can be used);
- calculations of coastal effects due to the run-up of the 'design' wave, which should take into account the quasi-monochromatic structure of the wave packet.

Acknowledgements

This study was supported for EP by grants from CNRS, RFBR(05-05-64265) and INTAS (03-51-3728).

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