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On the Possibility of Tsunami Formation as a Result of Water Discharge into Seismic Bottom Fractures

B. V. Levin[a] and M. A. Nosov[b]

[a] *Institute of Marine Geology and Geophysics, Far East Division, Russian Academy of Sciences, ul. Nauki 1b, Yuzhno-Sakhalinsk, 693022 Russia*

[b] *Moscow State University, Vorob'evy gory, Moscow, 119992 Russia*

e-mail: lbv@imgg.ru; nosov@phys.msu.ru

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Abstract—A fundamentally new mechanism of tsunami generation as a result of water discharge into rapidly opening seismic fractures of the bottom is proposed. A mathematical model of the phenomenon developed within the framework of the linear potential theory is presented. The main parameters of the problem that affect the characteristics of the formed wave are revealed.

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An elastic wave *P*, propagating in a solid medium at a velocity of a longitudinal wave, is radiated during an earthquake from the point of discontinuity origination, which is referred to as the hypocenter. This wave is followed by a transverse wave *S* with a lower propagation velocity and an amplitude exceeding that of the longitudinal wave. When the longitudinal (or compression) wave reaches the rock–air interface, the reflected extension wave is formed. The amplitude of the mass velocity of this wave (or the oscillatory velocity of particles in the wave) is twice as large as the amplitude in the initial compression wave *P*. Strong earthquakes with magnitudes $M > 7.5$ generate a longitudinal wave with a mass velocity exceeding 1 m/s near the epicenter [1, 2]. Recall that, if the mass velocities in the seismic wave are higher than 0.1 m/s, engineering constructions are damaged. According to our data [2], seismotectonic disturbances up to several hundreds of kilometers long with amplitudes of displacements exceeding 10 m are observed during catastrophic earthquakes with an oscillation intensity of 11 in zones of active faults.

During earthquakes with magnitudes $M > 8$, the mass velocity in the longitudinal wave can attain 5 m/s or more [2]. In a wave reflected from a free surface, the mass velocity can be about 10 m/s as a result of the effect of velocity doubling. It is known that discontinuities accompanied by numerous fractures and the accumulation of damage arise in most rocks during the passage of a compression–extension wave with an amplitude of more than 8 m/s.

The study of macroseismic effects of strong earthquakes [1, 2] and especially of those that occurred during the past 50 years [3–6], shows that seismic ruptures and fracture systems occupying vast areas are formed in epicentral zones or in pleistoseist zones (zones of the maximum intensity of shocks) of such earthquakes. The length of a single rupture attains several tens of kilometers (20 km during the 2003 Altai earthquake; 35 km during the 1995 Neftegorsk earthquake; 265 km (Bogdo fault) during the 1957 Gobi-Altai earthquake, when the total length of faults attained 850 km). Seismic ruptures are gaping fractures 3–15 m wide and up to 20–50 m deep. Often, a system of feather fractures of up to 500 m wide is formed in the main-rupture zone [3]. The typical fracture, which was formed during the 2003 Altai earthquake, is presented in Fig. 1. Note that the characteristic lengths of the pleistoseist zones of the strongest earthquakes, within which fracture systems arise, are about 1000 km, and the width of such a zone is about 100 km (for example, the earthquake in the Middle East and the earthquake of December 26, 2004, in Indonesia).

In the case of a strong submarine earthquake, all of the aforementioned effects must analogously develop in bottom rocks. A rapid opening of fractures and voids in rocks being in contact with the water layer provides conditions for an abrupt discharge (inflow) of water into the formed empty space. We should note that it is rather difficult to detect underwater fractures of seismic origin, because seismic profiling at large depths does not posses a sufficient resolution.

Under certain conditions (for example, shallow water), a complete bottom drying at a limited area is possible during a short time interval. According to the information received from an eyewitness of the Izmit earthquake (Turkey, 1999) and presented in [7], the aforementioned hypothetical discharge mechanism of tsunami generation was implemented in nature and

Fig. 1. Seismic rupture during the Altai earthquake more than 6 km long and up to 10 m wide. Photographed by E.A. Rogozhin.

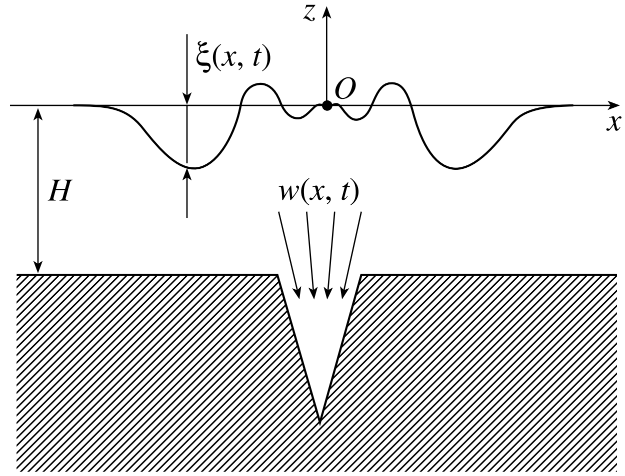

Fig. 2. Formulation of the problem about wave generation by a rapid water discharge into a fracture opening in the bottom.

had a living eyewitness. A Turkish fisherman who sat in a boat in a narrow and shallow strait near Cape Goelchuk (the Gulf of Izmit of the Sea of Marmara) felt an intense vibration (earthquake). Almost immediately, water started to go downward and his boat appeared to stand on the sea bottom. Vertical water walls about 15 m high stood at some distance on both sides of the bottom. Then, the water walls started to approach each other, large waves were formed, and the boat was carried out to the shore by a strong flow.

In scientific publications, such phenomena are usually called the Moses effect, by analogy with the well-known biblical story about the passage via the Red Sea. Of course, dried areas of the bottom exist during a short time, until water fills the entire volume formed by the developed fracture system. The effect of short-time drying of a Red Sea area during the Exodus and the hydrodynamic situation in which this phenomenon could be implemented were investigated in [8].

Evidently, in accordance with the discharge mechanism of tsunami generation, a leading wave of negative polarity (first ebb wave) is formed. It is known that many tsunamis, including the last catastrophic tsunami in the Indian Ocean in December 2004, began with the arrival of an ebb wave in a number of sites close to the source. It should be noted that such an effect can be caused by bottom subsidence in the tsunami-source region.

To reveal the main parameters controlling the amplitudes of waves caused by water discharge into a fracture formed in the bottom, we use a mathematical model developed within the framework of the linear potential theory of an incompressible liquid in [9]. The linear theory is based on the hypothesis that the wave amplitude is small compared to the ocean depth H. Note that water compressibility must be formally taken into account if the condition $\tau < 4H/c$, where τ is the time of fracture opening and c is the sound velocity in water, is fulfilled [10, 11]. However, for estimating the parameters of gravity waves, it is sufficient to use the theory of an incompressible liquid.

To estimate characteristics of the wave disturbance caused by a fracture opening in the bottom, it is reasonable to solve a two-dimensional problem in the vertical plane oriented perpendicularly to the fracture direction. Owing to the continuity condition, water will be drawn into the formed voids during fracture opening. Such a source can be described by specifying the vertical velocity at the bottom. The formulation of the problem is illustrated by the scheme presented in Fig. 2.

The origin of the orthogonal coordinate system Oxz is located on the undisturbed free surface of water, and the Oz axis is directed vertically upward. We will consider an infinite (along the Ox axis) layer of an ideal incompressible homogeneous liquid of a constant depth H in the gravitational field. Prior to the time $t = 0$, the liquid is at rest. To find the wave disturbance $\xi(x, t)$ that is formed on the liquid surface by a source (sink) at the bottom, where the vertical velocity of liquid flow is specified by the function $w(x, t)$, we will solve the problem for the flow velocity potential $F(x, z, t)$:

$$\frac{\partial^2 F}{\partial x^2} + \frac{\partial^2 F}{\partial z^2} = 0, \qquad (1)$$

$$g\frac{\partial F}{\partial z} = -\frac{\partial^2 F}{\partial t^2}, \quad z = 0, \qquad (2)$$

$$\frac{\partial F}{\partial z} = w(x, t), \quad z = -H, \qquad (3)$$

where g is the gravitational acceleration. We will choose the source function in the following simple form:

$$w(x, t) = -w_0[\theta(x + a) - \theta(x - a)] \times [\theta(t) - \theta(t - \tau)], \qquad (4)$$

where θ is the Heaviside step function, w_0 is the amplitude of the velocity of the liquid flowing into the fracture ($w_0 > 0$), a is the fracture half-width, and τ is the duration of source action. The sign "–" in formula (4) means that the bottom flow is directed vertically downward (oppositely to the Oz axis). In a general sense, during the opening of the fracture, its width and the flow velocity must vary in time; however (as will be clear from what follows), this is not a matter of principle and our considerations can be restricted to fixed values of these parameters.

The solution of problem (1)–(3) found by the method of integral transformations in [9] is given by the following formulas:

$$\xi(x, z, t) = \varsigma(x, t)\theta(t) - \varsigma(x, t - \tau)\theta(t - \tau), \qquad (5)$$

$$\varsigma(x, t) = -\frac{2w_0}{\pi}\left(\frac{H}{g}\right)^{1/2} \times \int_0^{+\infty} dk \frac{\cos kx \sin ka \sin(t(k\tanh k)^{1/2})}{k(k\tanh k)^{1/2}\cosh k}, \qquad (6)$$

where the integrands are dimensionless quantities, whereas the coefficient before the integral is dimensional. The passage to dimensionless quantities is performed in accordance with the following formulas (hereinafter, the sign * is omitted):

$$k^* = Hk, a^* = a/H, x^* = x/H, t^* = t(g/H)^{1/2}, \tau^* = \tau(g/H)^{1/2}.$$

Obviously, in most cases, the fracture width is much smaller than the ocean depth $a \ll H$. The integrand in formula (6) rapidly decreases; therefore, the integration is actually performed not to infinity but to a certain finite limit k_{max}. Under the condition $k_{max}a \ll 1$, expression (6) can be represented as

$$\varsigma(x, t) = -\frac{2w_0}{\pi}\left(\frac{H}{g}\right)^{1/2}\frac{a}{H} \times \int_0^{+\infty} dk \frac{\cos kx \sin(t(k\tanh k)^{1/2})}{(k\tanh k)^{1/2}\cosh k}. \qquad (7)$$

Additionally, if the fracture opening is treated as a rapid process, i.e., $\tau \ll (H/g)^{1/2}$, a further simplification is possible:

$$\xi(x, t) = -\frac{2}{\pi}\frac{w_0 a\tau}{H}\int_0^{+\infty} dk \frac{\cos kx \cos(t(k\tanh k)^{1/2})}{\cosh k}. \qquad (8)$$

Formula (8) suggests that the amplitude of the tsunami wave generated by water discharge into the fracture is proportional to the fracture cross section area ($S \sim w_0 a\tau$) divided by the ocean depth H.

It is seen that the ocean depth is the most important parameter controlling the effectiveness of the discharge mechanism of tsunami generation. We analyzed the ocean-depth distributions in the epicenters of the known tsunamigenic earthquakes of the Pacific region (in all, 1096 events). The coordinates of epicenters are taken from the historical database on tsunamis in the Pacific Ocean compiled at the ?IVMiMG SO RAN (http://tsun.sscc.ru/htdbpac). The ocean depth was calculated in accordance with the ETOPO2 global database on the Earth's relief (http://www.ngdc.noaa.gov). It has been established that the depth at the epicentral point is smaller than 200 m nearly in the half of cases (48%).

Let us estimate the amplitude of the wave generated by a relatively small isolated fracture with the half-width $a = 1$ m and the depth $w_0\tau = 10$ m. If the ocean depth is $H = 100$ m, the wave amplitude will be 0.1 m. This value can substantially increase for a fracture system or for a larger-scale fault. Traditional mechanisms of tsunami generation yield similar values of the wave amplitude in the source.

The wave packet formed during the discharge into an isolated fracture will be dispersive, and the largest wavelength will approximately correspond to the ocean depth. For long times (or large distances from the source) and $x < t$, the integral of (8) can be represented with the use of the method of stationary phase

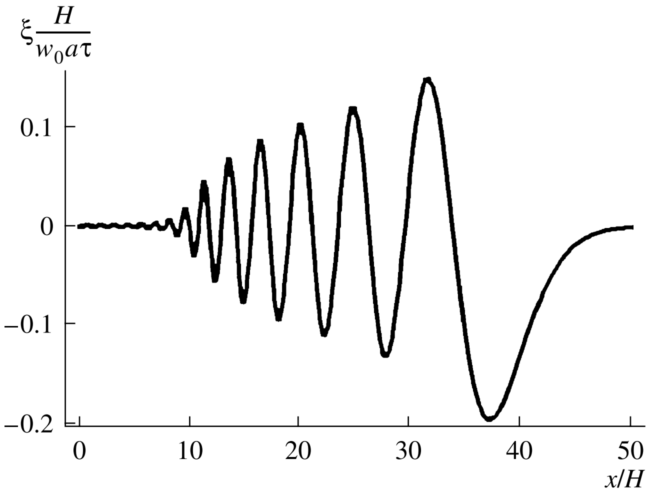

Fig. 3. Form of the wave generated by a rapid water discharge into a narrow isolated fracture. The calculation is performed for $t = 20$.

[12]. For example, if $x > 0$, the asymptotic representation of formula (8) has the following form:

$$\xi(x, t) = -\frac{1}{\pi}\frac{w_0 a\tau}{H}\sqrt{\frac{2\pi}{x|S''(k_0)|}}\frac{1}{\cosh k_0} \times \cos\left[t(k_0 \tanh k_0)^{1/2} - k_0 x - \frac{\pi}{4}\right], \tag{9}$$

$$\text{where } S(k) = \frac{t}{x}(k \tanh k)^{1/2} - k.$$

It is seen from formula (9) that the wave amplitude will decrease with the distance in accordance with the law $\xi \sim x^{-1/2}$.

The typical form of a wave disturbance resulting from a narrow fracture that abruptly opened in the bottom is presented in Fig. 3. The leading wave is negative, and it is followed by a dispersive train.

The performed analysis of hydrodynamic processes arising in a body of water above an opening bottom fracture confirms that the formulation of the problem about the discharge mechanism of tsunami generation is rightful, and that a further study of this mechanism within the framework of improved models with invoking numerical and physical experiments is promising.

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