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Numerical modeling of the resonant tsunami generation by the submarine landslide*

An.G. Marchuk

Abstract. The problem of the tsunami wave generation by the submarine landslide, which is moving along the bottom slope, is studied. A number of numerical experiments were carried out for a model submarine landslide. A maximum amplitude and the wavelength were defined for various landslide profiles and their moving rates. As expected, the highest waves are generated when the velocity of the submarine mudslide is equal to the long wave propagation velocity. The landslides, which are moving slower and faster than the resonant one, generate waves with a lower amplitude and a bigger wavelength. The generated waves have a fairly expressed directivity of radiation.

1. Introduction

Currently, many scientists are studying the landslide mechanism of tsunami generation (see, for example [1–4]). Now it is clear that a lot of historical tsunamis were generated by submarine landslides (mudslides), which were initiated by earthquakes. One of the greatest tsunamis of the last decade of the 20th century near Papua and New Guinea (1998) was generated by a huge submarine landslide. The latter was triggered by rather a weak earthquake. Another well-known event is the Aleutian tsunami of 1948. The mystery of abnormal wave amplitudes was discovered only 50 years after this event. Now it is clear that such high tsunamis could not be generated directly by such a weak earthquake. Huge tsunami waves, which attacked the Hawaiian coast, were generated by the submarine landslide that occurred just after the earthquake [2]. Such a disastrous phenomenon could take place where a big amount of sediments are accumulated above the steep bottom slope. The landslide (mudslide) movement can be a result of the ground shaking by an earthquake. The velocity of the sliding mass during this process is not very big and theoretically can be close to the long-wave propagation velocity at the locality. For example, if the motion of the sliding mass along the bottom slope starts near the water edge, the sliding velocity and the tsunami propagation velocity are both proportional to the square root of the depth value. A certain ratio between the density of the sliding material and the bottom slope angle can result in proximity of both propagation velocities.

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2. The resonant long wave generation

Due to the water incompressibility, every instant a bottom displacement causes a similar water surface displacement. When such a displacement is horizontally moving, some resonance effects can be observed on the ocean surface. If the bottom displacement (a sliding body) moves too slow, then the surrounding water will be redistributed around this body and no significant wave will be generated. In the late 70s, the tsunami generation by moving bottom displacements was studied using numerical computations [5]. The main object of that study was the directivity of wave radiation.

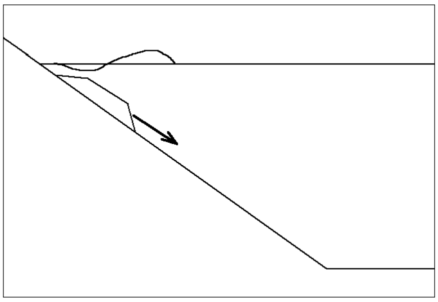

Figure 1. The process of tsunami generation by the submarine landslide

It is known [6] that the long wave (tsunami) propagation velocity is given by the Lagrange formula

$$c = \sqrt{gH}, \qquad (1)$$

where g is the gravity acceleration and H is a depth value. Let the bottom be a uniform slope with the inclination angle equal to α. The scheme of the generation process is shown in Figure 1. If the motion of a sliding mass of the density ρ starts just near the water edge point, its acceleration along the slope surface caused by the gravity force will be expressed as

$$a = g\frac{\rho - 1}{\rho}\sin\alpha. \qquad (2)$$

Here the water density is assumed to be equal to 1 g/cm^3. The total route of sliding body can be expressed as $\frac{at^2}{2} = \frac{H}{\sin\alpha}$. After multiplication of the both parts of this equation by the value of acceleration a, we have

$$\frac{a^2t^2}{2} = \frac{\left(\frac{V_x}{\cos\alpha}\right)^2}{2} = \frac{H}{\sin\alpha}a = \frac{H}{\sin\alpha}g\frac{\rho-1}{\rho}\sin\alpha.$$

The horizontal velocity of the mudslide without friction forces is given by the formula

$$V_x = \cos\alpha\sqrt{2gH\frac{\rho-1}{\rho}}. \qquad (3)$$

The resonant wave generation is realized when the horizontal component V_x is close to the wave propagation velocity $\boldsymbol{c}$ (see (1)). The condition of the resonance can be expressed as follows:

$$2\frac{\rho - 1}{\rho}\cos^2\alpha = 1. \tag{4}$$

Condition (4) can be fulfilled for a wide range of parameters, for example, $\rho = 3$ and $\alpha = 30°$. So, if the sliding mass is moving down the bottom slope as a solid body due to the only gravity, the horizontal projection of the mudslide velocity can sometimes be very close or exactly equal to the tsunami propagation velocity, given by formula (1).

3. Numerical simulation

Let us study the process of the tsunami wave generation by the rectangular bottom elevation with a trapezoidal profile, which moves along the flat bottom surface. The profile of the bottom displacement is shown in Figure 2. A numerical model of the generation process is based on the shallow-water model and was developed by V. Titov [7]. A series of numerical experiments were carried out for various inclination angles of the frontal part of the trapezoid and different values of the displacement velocity. In order to study common features of the generation process, the numerical experiments were carried out in the square computational area with a constant depth (1000 m). The size of the whole area was taken as 50×50 km. The moving bottom displacement has dimensions 10×10 km and the computational grid steps were equal to 100 meters in both directions. The whole length of the displacement L was constant in all computations and was equal to 10 km. The elevation value h was also constant and equal to 1 meter. The velocity of the displacement movement V and the width of the displacement slope L_1 (see Figure 2) were varying during a series of the numerical experiments.

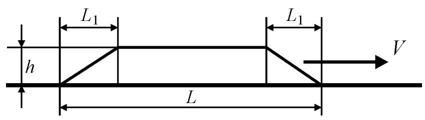

Figure 2

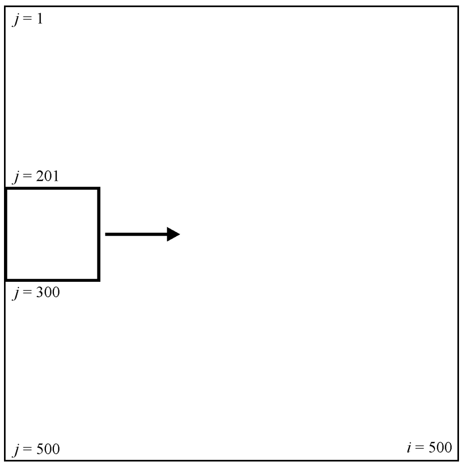

Figure 3. Overview of the computational area

At the initial time step, this bottom elevation is located between $i = 1$ and $i = 101$ grid-points in X direction and between $j = 201$ and $j = 300$ grid-points in Y direction (Figure 3).

Table 1 presents a maximum wave height $h_{\max}$ and the length of the leading tsunami wave l in the case of the resonance ($V = 99$ m/s) at 100,

Table 1

L_1, km	$t = 100\,\text{s}$		$t = 200\,\text{s}$		$t = 300\,\text{s}$		$t = 400\,\text{s}$	
	$h_{\max}$, cm	l, km	$h_{\max}$, cm	l, km	$h_{\max}$, cm	l, km	$h_{\max}$, cm	l, km
10	540	2.4	1017	2.6	1390	2.8	1677	3.0
20	282	3.2	549	3.4	770	3.6	955	3.8
30	173	4.1	369	4.2	517	4.3	639	4.4
40	143	5.0	278	5.2	389	5.3	480	5.4

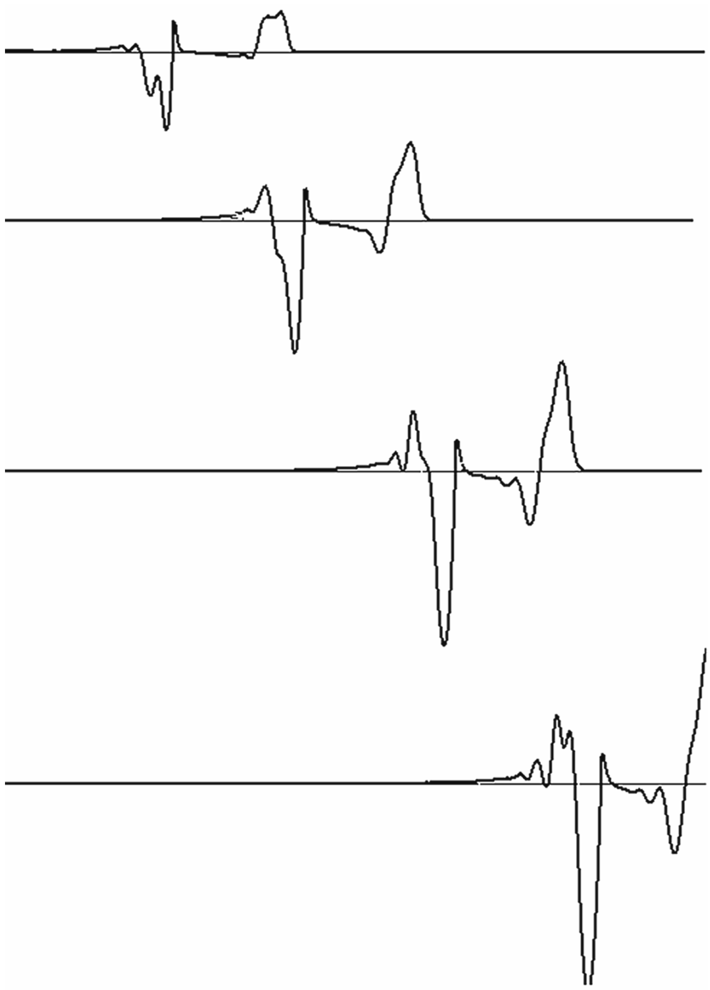

Figure 4. The profile of the water surface at 100, 200, 300 and 400 seconds after the beginning of the process

200, 300, and 400 seconds after the start of the generation process. Here, the width L_1 was equal to 10, 20, 30, and 40 km, respectively.

Figure 4 shows the water surface profiles along the line $y = 25$ km (the trace of the moving bottom displacement center). The upper profile shows the wave profile at the time moment of 100 s. The other profiles present the surface at 200, 300 and 400 seconds after the start.

Table 2 shows a maximum height and the wavelength of the leading wave l at the time of 200 s. Here, the parameter L_1 was equal to 2000 m. The relative landslide velocity (V/c) was varying from the value 0.8 to 1.2.

Table 2

V/c	0.8	0.9	1.0	1.1	1.2
$h_{\max}$, cm	138	325	552	520	331
l, km	6.0	4.3	3.3	3.6	4.9

According to Tables 1 and 2, one can conclude that the highest wave is generated by the bottom displacement, which is moving with the “resonant” velocity ($V/c = 1$). The mudslides with steeper fronts can produce the higher waves, but the wavelength is almost linearly dependent on the width of the bottom displacement front slope L_1. The landslides, which are moving faster or slower than the resonant one, generate the longer waves. One more characteristic feature of this process can be formulated as a fairly expressed directivity of the wave energy radiation. The resonant mudslide generates a very wide tsunami front, which is almost flat. In this case, most of the whole wave energy is radiating in the direction of the slide motion (Figure 5).

In Figures 6, the results of numerical simulation of tsunami generation by a submarine mudslide are presented. Here, the bottom slope was twice shorter than the computational area length. The 500×500 grid-points computation area and the shape of submarine landslide are shown in Figure 3.

Let us go back to the tsunami of April 1946. A comprehensive study of this event is presented in [2]. The main objective of this paper is to prove the submarine landslide genesis of this tsunami event. In Figure 7, borrowed from [2], a possible place of landslide is indicated by a black curve. According to this image, which was obtained by multibeam measurements [8], the submarine landslide, which causes the major tsunami, starts at the shelf edge (where a depth is about 500–1000 m) and stops at the Aleutian terrace, where a depth is about 4000 meters.

The next figure, also taken from [2], shows the measured tsunami wave heights all around the Pacific. The digits in black circles mean tsunami wave heights. It is clearly seen that the main part of the wave energy was radiated to the south of the Aleutians. In Figure 8, this direction is indicated by the long grey arrow.

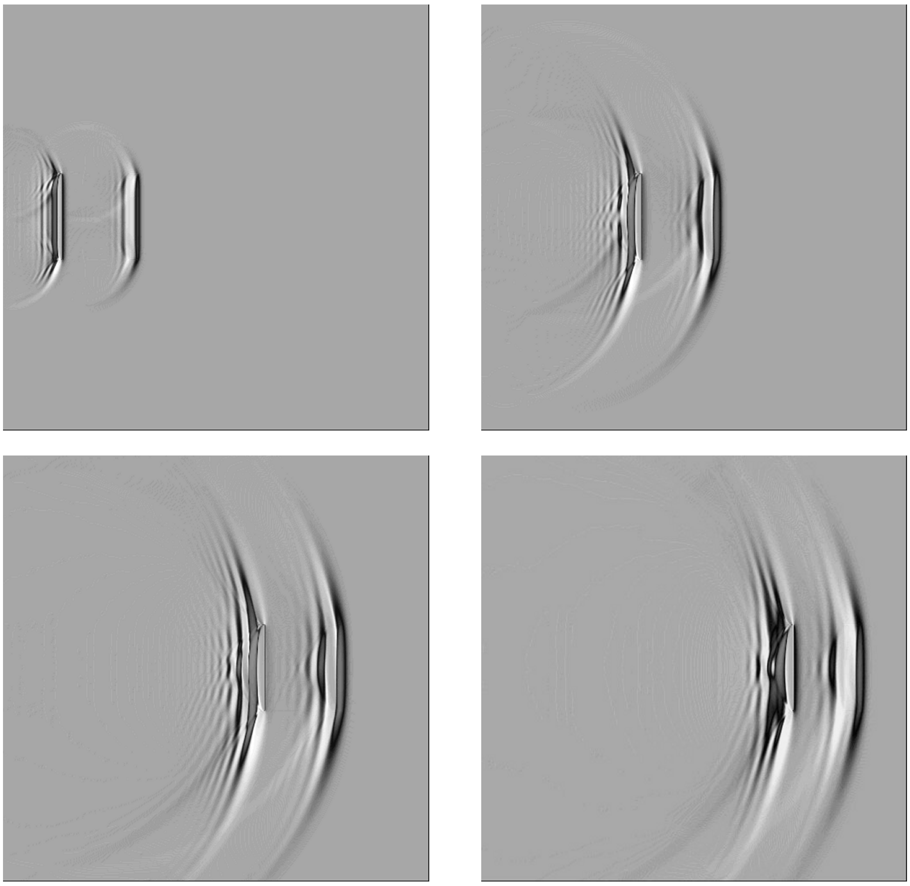

Figure 5. The directivity of the wave energy radiation

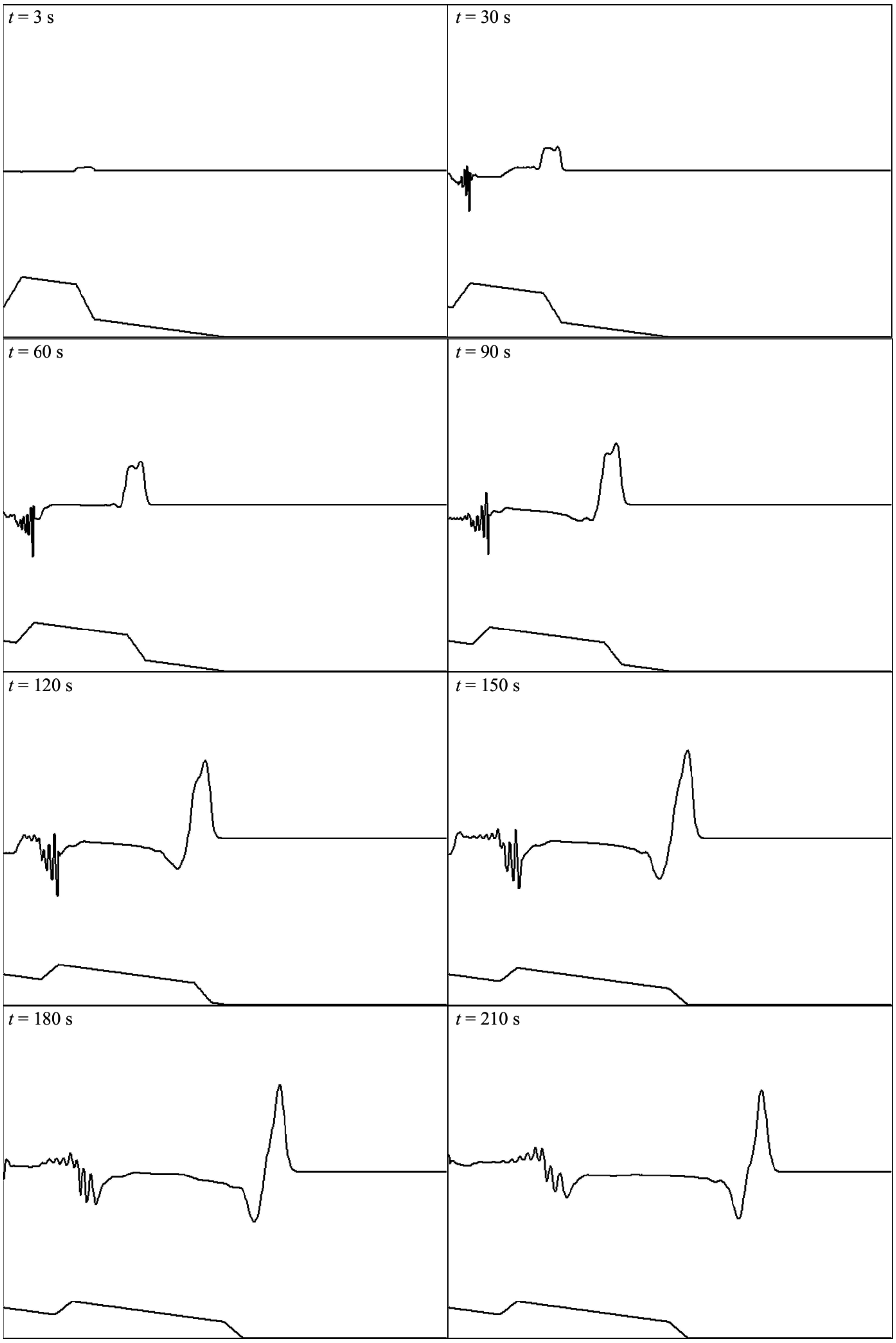

Figure 6. Tsunami generation by submarine landslide above the limited bottom slope

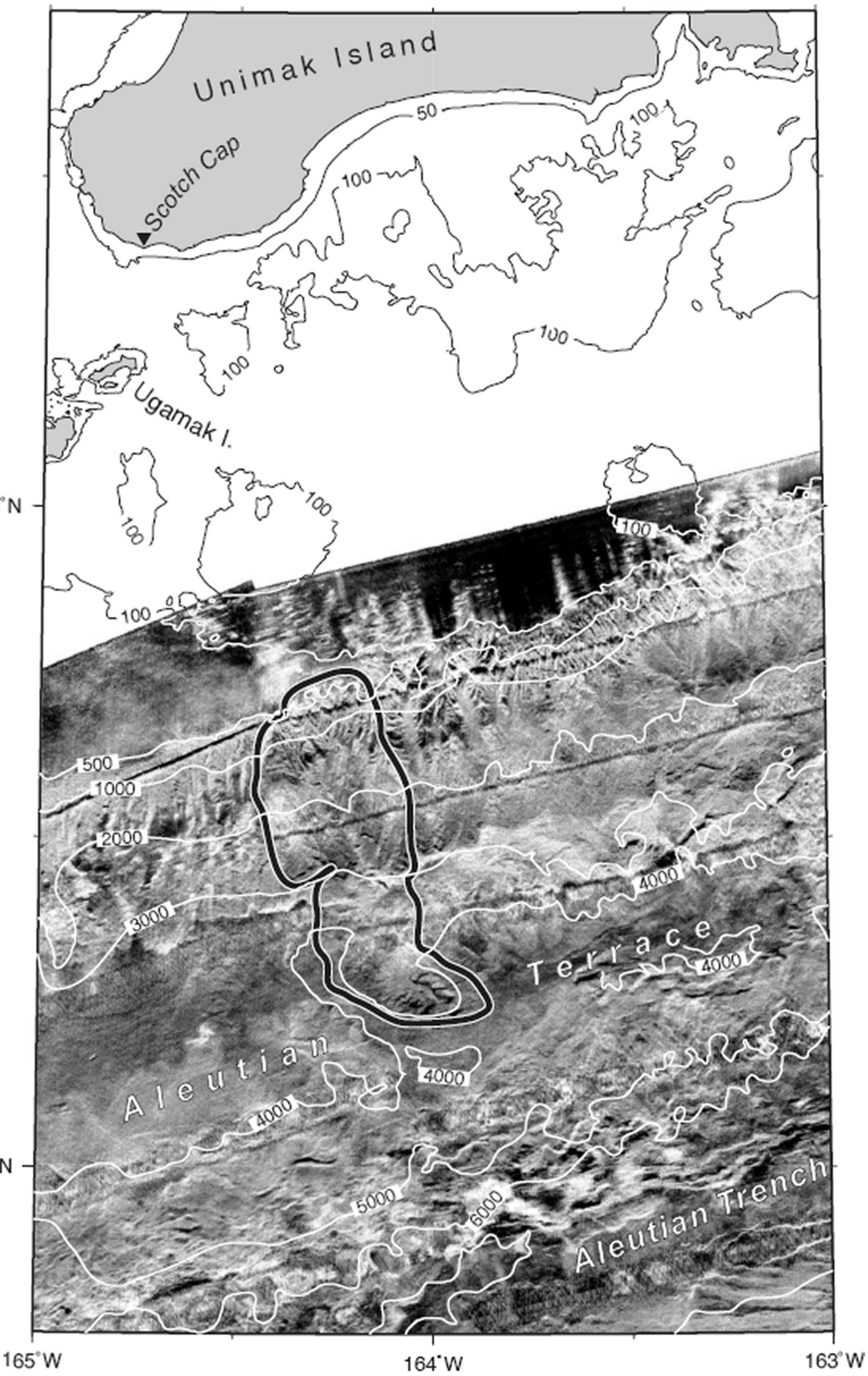

Figure 7. The bottom relief near the Ugamak island [6]

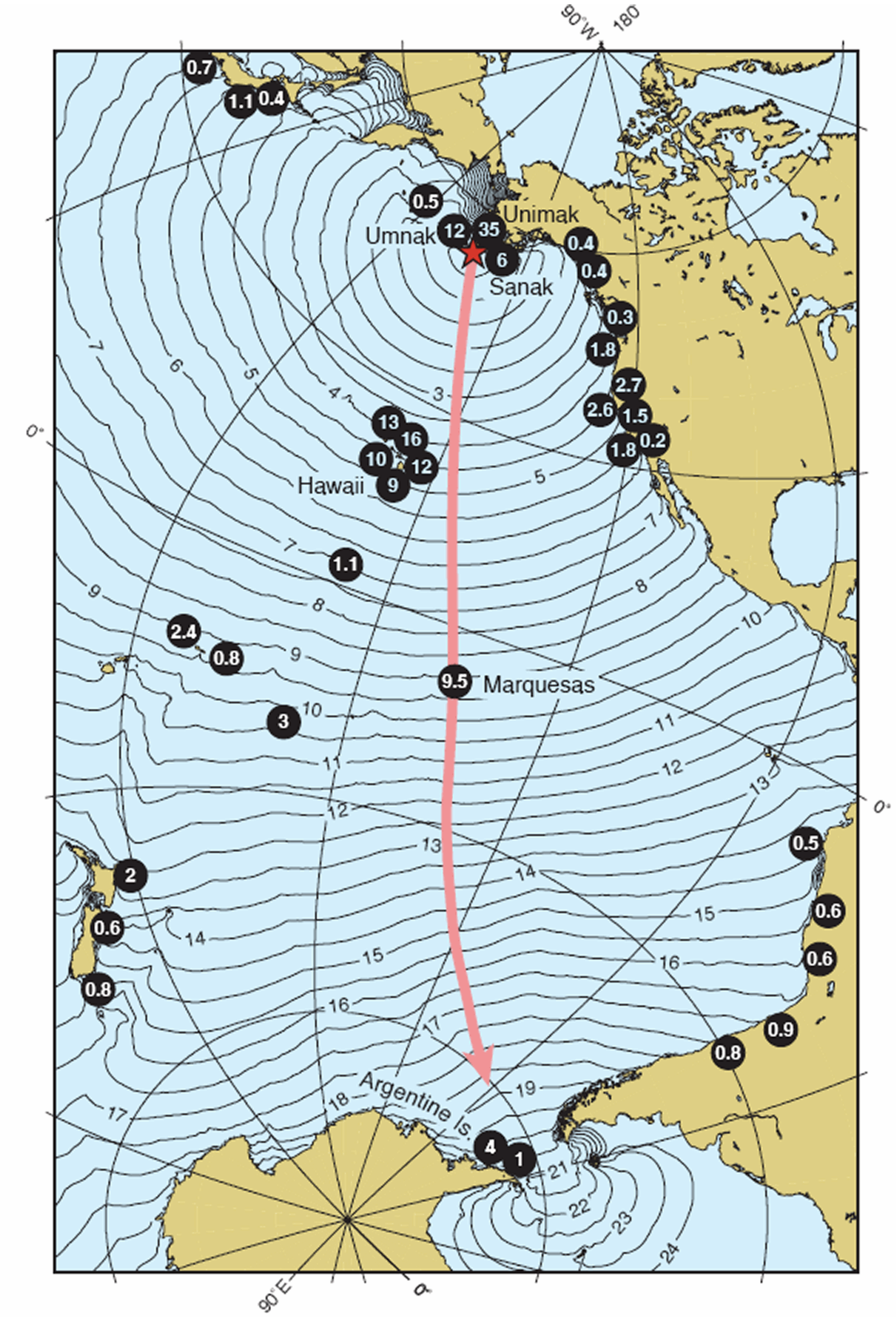

Figure 8. Measured tsunami heights during the Ugamak tsunami of 01.04.1946

Various scenarios for the submarine landslide tsunami generation with different kinds of the mudslide structure were studied in [2]. But none of them can explain a sharp directivity of the wave energy radiation. The possible way of such a directivity of the wave energy radiation is the resonance effect, which was studied earlier in this paper.

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