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Numerical modeling of the long wave passing above the submerged barrier*

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Abstract. The new method for the numerical simulation of partial reflection of the long waves off the submerged vertical barrier was developed and tested. This method is based on the inner boundary condition which takes into account the wave energy loss due to such a kind of reflection. The method was implemented into the MOST numerical algorithm which have been used for estimation of the submerged barrier protection ability against tsunami wave entering the Oppa harbor.

1. Introduction

The only way to protect the oceanic coast or, at least, to reduce the damage of tsunami impact is in constructing massive walls to separate the ocean and infrastructure districts. The breakwaters surrounding a port water area serve the same goal. However, such constructions have often been damaged or even broken as a result of major tsunamis. This happens due to the huge pressure force aiming at breakwater blocks in the process of major tsunami. The breaking force is proportional to the height of such a vertical construction. As an example, Figure 1 presents the location and ruins of the northern seawall (breakwaters) at the entrance to the Kamaishi harbor, Iwate pref., Japan as a result of 11.03.2011 tsunami impact [1]. The scheme of the damage from the breakwaters across the Kamaishi harbor entrance [2] is shown in Figure 2.

As the momentum flux density tensor is proportional to the squared velocity [3], it is natural to try to reduce the wave impact strength and the resulting damage by reducing the fluid velocity, for example, by placing an obstacle across the fluid path. The results of laboratory experiments in the early 1960s have shown that an obstacle crossing the path of a strong tsunami reduces not only the wave run-up height but also the velocity of the onshore water mass flow. One engineering solution for sheltering the population and infrastructure from tsunamis is constructing of protective walls of various kinds separating harbors from the main territory of settlements and towns (Figure 3). The height of such walls reaches 5 m.

Another solution is a massive wall with a narrow entrance at the mouth of harbors. Figure 4 presents a snapshot of a protective pier in the Ofunato

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Figure 1

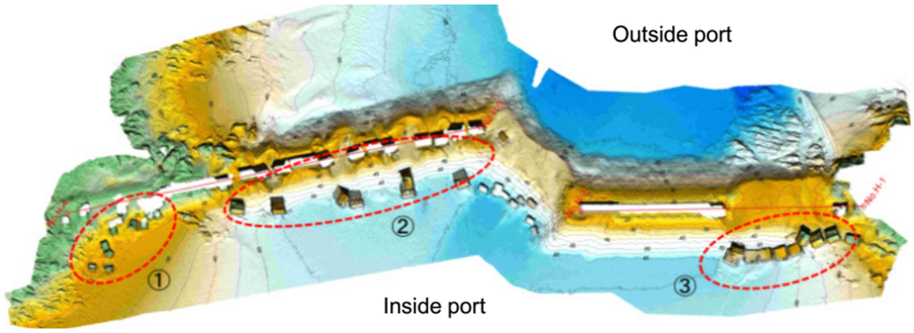

Figure 2. Tsunami-distributed caissons of the breakwaters in the Kamaishi Port: 1 — a shallow water section of the north breakwater, 2 — a deep water section of the north breakwater, and 3 — a part of the south breakwater

Figure 3. The five-meter high gates at the entrance to the Shizuoka port

Figure 4. Sea wall at the entrance to the Ofunato bay

Bay (Japan) (the total pier length is 740 m, leaving a 200 m wide entrance to the bay), capable of withstanding tsunamis up to 6 m in height (underwater barriers). In addition, there is a submerged barrier across the "Central gate" of this construction.

Built in 1967, the Ofunato breakwaters proved their efficiency just one year later during the tsunami of May 16, 1968, twofold reducing the tsunami height. Such barriers are, in principle, capable of protecting the harbor constructions against a tsunami of moderate strength, but for a strong event, even solid concrete walls rising above water contribute to the tsunami water head and toppled over. During the strong tsunami of 1983, water flowed above walls 6 m in height in the Noshiro harbor, and several blocks weighting 5,000 t each were overturned (Figure 5).

Consequently, from this standpoint, it is advisable to use one or several submerged barriers that do not fully suppress tsunamis but substantially

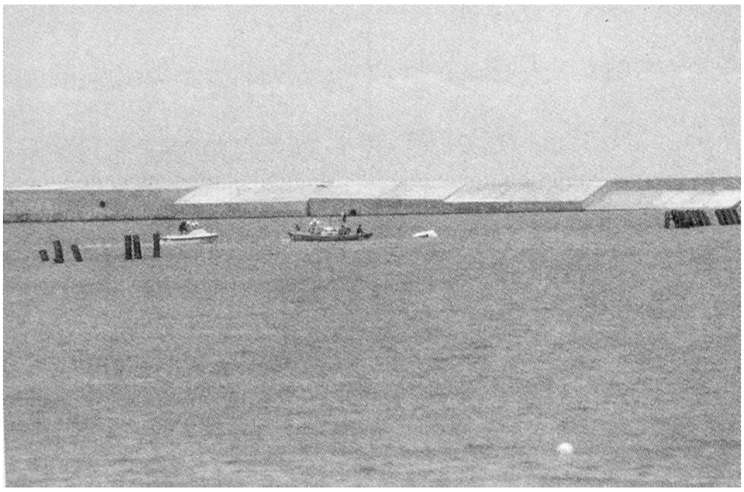

Figure 5. Overturned blocks of the Noshiro port breakwaters as a result of the 1983 tsunami impact

mitigate their hazard to the seacoast communities. An indirect evidence in favor of such an approach is provided by the recently published data on a substantial mitigation of destructive tsunami consequences in the zones on the shore that are protected by coral reefs. Conversely, in the locations where the reefs were damaged or fully destroyed through illegal trade, the damage caused by tsunamis was particularly devastating. Based on multiple data sources [4], the International Maritime Organization indicated to an important role of the submarine coral reefs in protecting against tsunami disasters. Theoretical and numerical models of the response from a vertical unsubmerged barrier to the propagation of a traveling tsunami wave have been under study since the 1960s (see [5–9]).

2. Simulation of a long wave passing above a submerged barrier

The suppression ability of a submerged vertical barrier is lesser than the above-surface one, but it is steadier because of a significantly smaller water pressure when a stream is stopped by it. With the assistance of the laboratory at the University of Tel Aviv, the experiments on a hydrodynamic flume on the long wave suppression by underwater vertical barriers were carried out. Experiments described in [10] showed good results for impacting submarine barriers on tsunami wave propagation but actually very expensive.

Let us now quantitatively assess the parameters of a wave in the process of its pass over the submerged vertical barrier. We assume that the water layer from bottom to top of the underwater barrier is stopped by this barrier, and the water layer which is above the upper edge of a barrier continues its horizontal movement (Figure 6). It is known from hydrodynamics [11] that in a moving long wave, the kinetic energy E_K is equal to the potential E_P:

$$E_K = \int_0^L \frac{\rho u^2}{2}(D+\eta)\,dx = \int_0^L \frac{\rho\eta^2}{2}\frac{g}{(D+\eta)}(D+\eta)\,dx = \int_0^L \frac{\rho\eta^2 g}{2}\,dx = E_P,$$

where L means the wavelength, ρ is the fluid density, u is the horizontal flow velocity, D is the depth, η is the surface elevation above the zero level, g is the acceleration of gravity. Here we see that the wave height and the flow velocity in the running long wave is proportional to the square root of its energy.

After tsunami has passed a wave above the submerged vertical barrier, it loses a part of its kinetic energy, approximately, equal to the barrier height relative to the ocean depth. To be exact, it is equal to the sum of the depth and the height of this wave in front of the barrier.

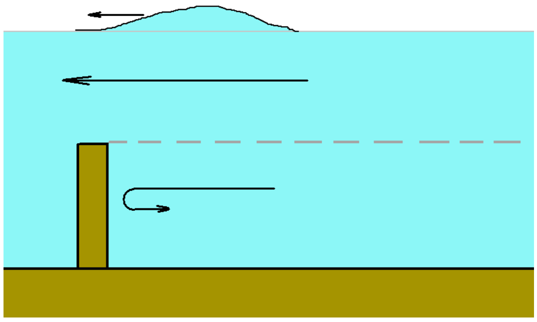

Figure 6. A scheme of the water flow direction when the tsunami wave passes above the submerged vertical barrier

Let us assume that the wave of height h_1 passes over the submerged barrier having the height H installed at a depth of D. In this case, the total wave energy E_2 after passing the barrier will be expressed as

$$E_2 = E_1\Big(\frac{1}{2} + \frac{1 - D/H}{2}\Big),$$

where E_1 is the total wave energy before a barrier. As a result we come to the formula for the long wave height h_2 after the wave has passed the underwater vertical barrier

$$h_2 \approx h_1\sqrt{\frac{E_2}{E_1}} = \sqrt{\frac{2 - D/H}{2}}. \qquad (1)$$

For example, with a relative height of a barrier of about 0.75, a part of the total wave energy to be reflected from a barrier exceeds 20 percent.

The numerical simulation of the long wave propagation over the submerged barrier was carried out within the differential shallow water model:

$$\begin{aligned} H_t + (uH)_x + (vH)_y &= 0,\\ u_t + uu_x + vu_y + gH_x &= gD_x,\\ v_t + uv_x + vv_y + gH_y &= gD_y, \end{aligned}$$

where $H(x, y, t) = h(x, y, t) + D(x, y, t)$, h is the water surface displacement, D is the depth, $u(x, y, t)$ and $v(x, y, t)$ are the horizontal flow velocity components along the axes x and y, g is the acceleration of gravity. The numerical algorithm for solving this problem has been developed in the Novosibirsk Computing Center and is titled “MOST” [12, 13].

Following (1), for the numerical simulation of partial reflection of a wave from a submerged barrier, it is sufficient at each time step of the grid point located just behind a barrier to forcibly establish the value of the water flow velocity u equal to the velocity before a barrier multiplied by the right-hand side of formula (1). For example, if the barrier height is twice lower than the depth, the water flow velocity behind the submerged barrier must be set as $v_2 = v_1\sqrt{0.75}$.

3. Numerical experiments

Let us test the method proposed on the 1D long wave propagation above the submerged vertical barrier. Figure 7 presents the one-dimensional passing of the 1-meter high tsunami wave above the 10 m high submerged barrier. The uniform depth of this 1D computational domain was equal to 20 m.

The ratio between the initial, the passing and the reflecting wave height is well correlated with the energy estimation and the results of laboratory experiments. Figure 8 presents a part of the height loss when the wave passing the underwater barrier is installed in the 11 cm water flume [10].

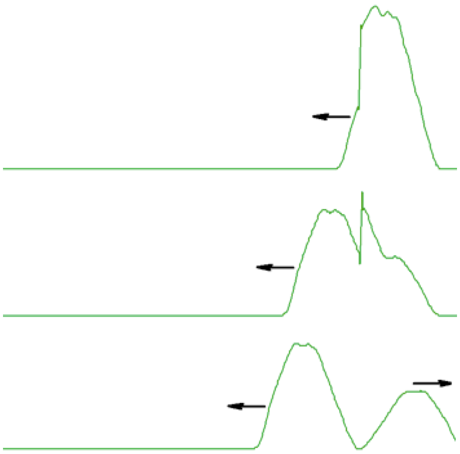

Figure 7. Snapshots of the long wave passing the submerged barrier

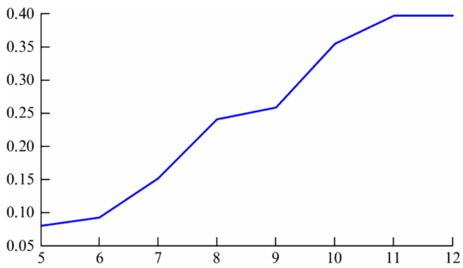

Figure 8. Relation between the barrier height (horizontal axis) and the wave suppression coefficient

In the two-dimensional case, the water surface just after the partial reflection of 1 m high tsunami wave by 1,700 m wide, and the 30 m high submerged barrier is shown in Figure 9. In this case, the value of the uniform depth is equal to 60 m.

Computations were carried out on a sequence of grids with various resolutions where one is embedded into another. Tsunami wave parameters are transferred from a larger domain to the embedded smaller one by means of the boundary conditions. The results presented in this paper are shown for the last stage of this process. Accordingly, the 2148×1074 nodes gridded bathymetry was created for the Oppa Bay and the neighboring harbors. The grid resolution is approximately 17 m. These data cover the geographical area from 141.41659° E to 141.75° E and from 38.5° N up to 38.6666° N.

A number of numerical experiments with a submerged barrier located at the entrance of the Oppa harbor were carried out. Figure 10 presents a snapshot of the tsunami entering the Oppa harbor. The position of the 1700 m wide submerged barrier is shown as a black line segment. This

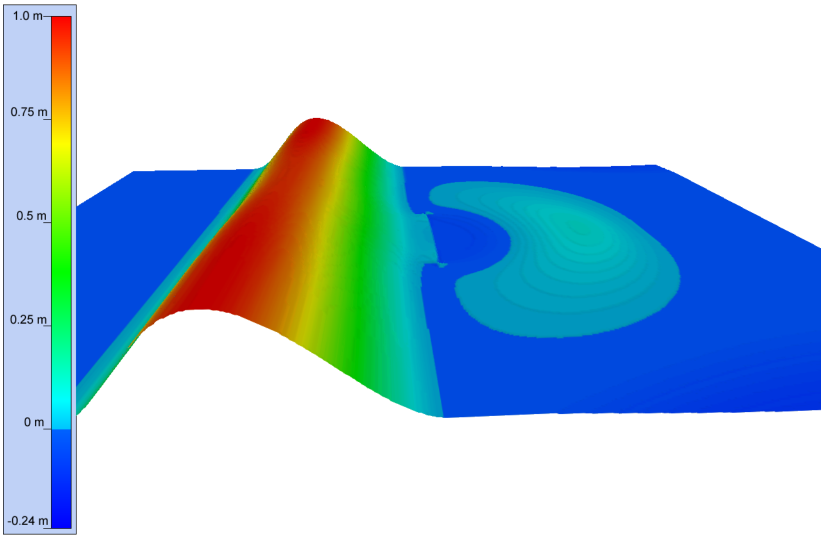

Figure 9. The partial reflection of the 2D wave of one meter high by the narrow submerged barrier. All the values of water elevation in the legend are indicated in centimeters

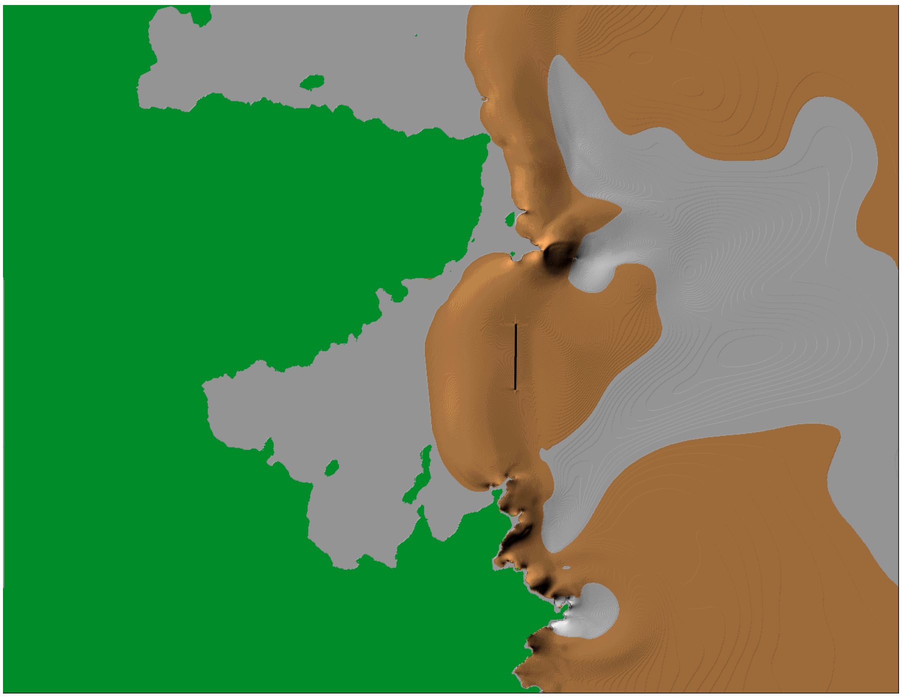

Figure 10. The water surface displacement inside the Oppa harbor during the modeling tsunami propagation above the virtual submerged barrier

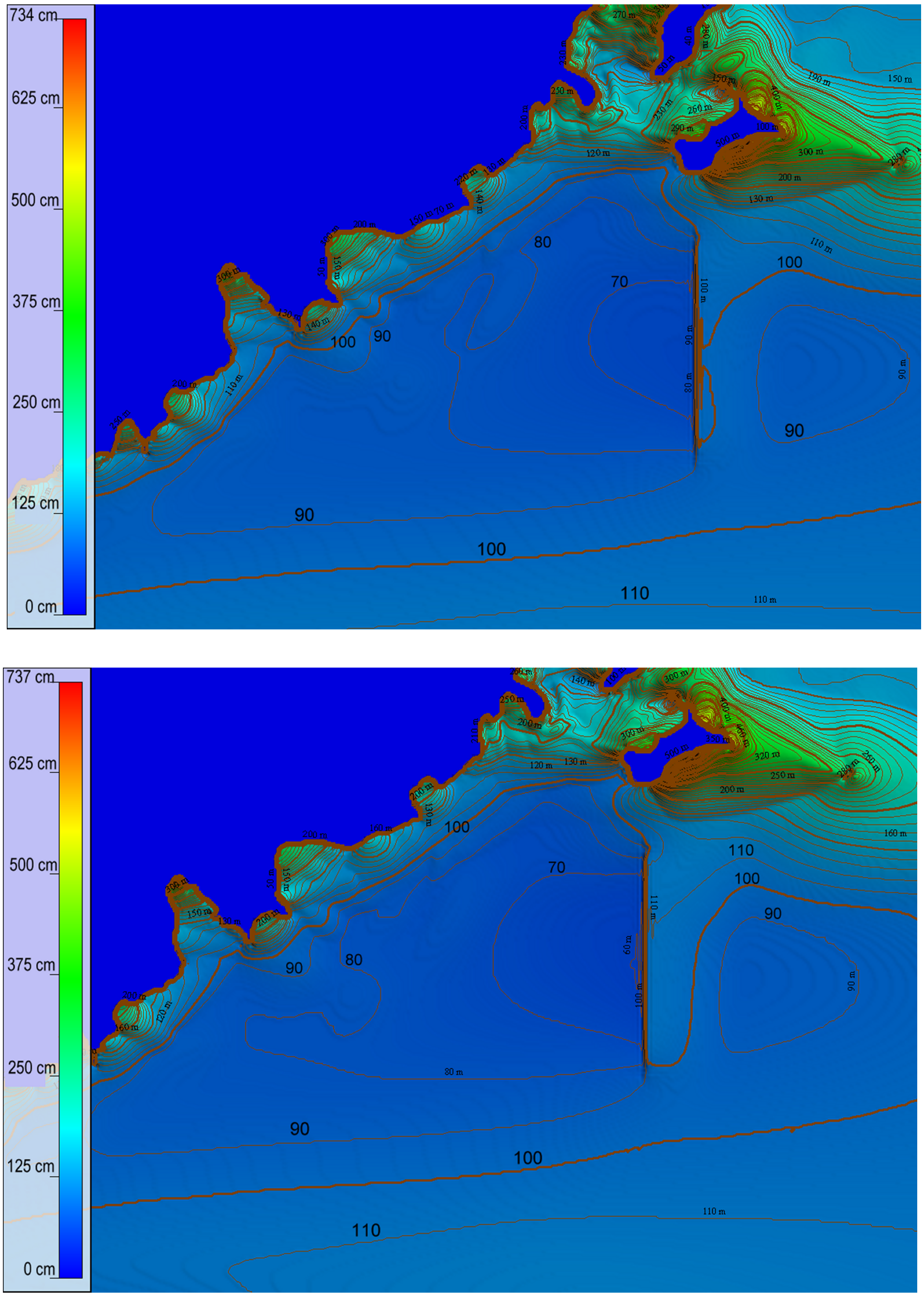

Figure 11. Distribution of the wave height maxima (in cm) in the northern part of the Oppa harbor after the tsunami wave passing above the submerged barrier of 0.5 (top) and 0.75 (bottom) ocean depth

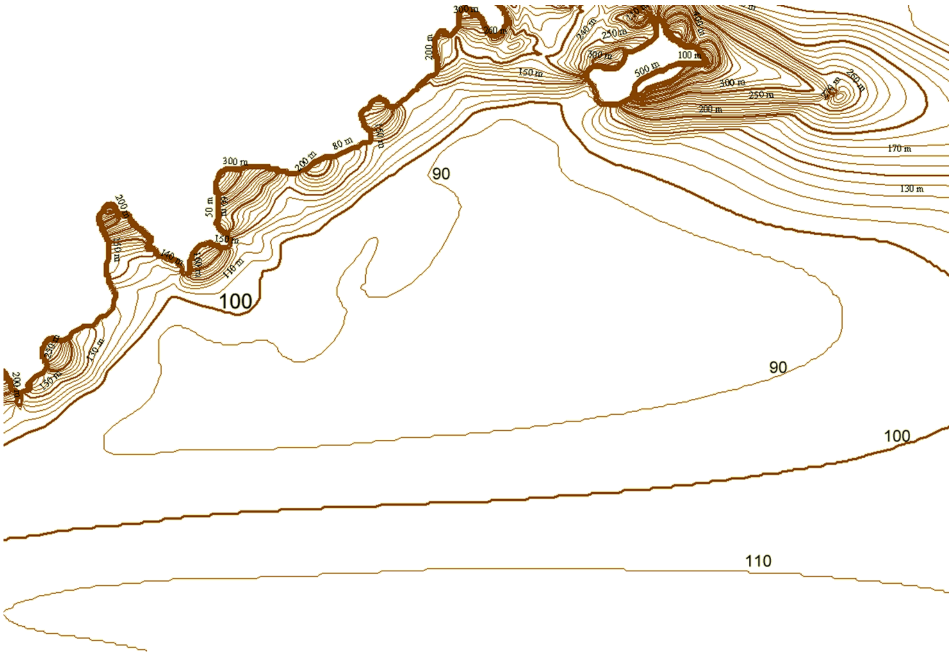

Figure 12. Distribution of the wave height maxima in the northern part of the Oppa harbor as a result of the tsunami wave propagation without any barrier

barrier is installed on the bottom, where depth is approximately 60 m and its height is equal to 30 m. Here the initially flat 1 meter high tsunami wave propagates from the right boundary of 1400x980 knots computational domain. The brown color shows the positive water surface or the dry land elevation, and the grey color means the suppression or the mean water level. In further numerical experiments, the barrier was shifted to the northern part of the Oppa harbor entrance. The depth at the barrier location varies from 60 m at its southern edge up to 20 m at the northern. All along the barrier its height is equal to the half the local depth.

Figures 11 and 12 present isolines of the wave maxima in the northern part of the Oppa harbor as a result of 100 second period of the tsunami wave passing above submerged barrier whose height is 0.5 and 0.75 of the ocean depth high barrier (Figure 11) and without any barrier (Figure 12). In all these figures, the isoline levels are marked in centimeters.

After analyzing Figures 11 and 12, we can resume that the wave heights in the northern part of the Oppa harbor with a relative barrier height were reduced (suppressed) by 0.8 as compared to the wave height distribution without any barrier. In the case of the barrier height be equal to 0.75 of a local depth, the tsunami height reduction ratio decreases down to approximately 0.65. In order to protect some crucial coastal objects, we can vary the position, width or the height of virtual submerged barriers choosing the desired mitigation effect.

Conclusion

The results of the one-dimensional and the two-dimensional calculations of the long wave passing above the submerged vertical barrier have shown compliance of the ability suppressing the earlier carried out laboratory experiments in the hydrodynamic flume. The simulation of the partial reflection of a tsunami wave from an underwater barrier on a real bathymetry has shown a sufficiently protective effect of such objects. The wave run-up height on some sites of the coast was reduced by 2–3 meters. Thus, the sufficient protection ability of underwater barriers, whose stability is much higher than the seawalls towering over the water surface, is shown.

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