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Numerical and laboratory methods of tsunami waves modeling

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Abstract. Tsunami waves are one of the most destructive natural phenomena. The study and modeling of tsunami waves can allow us to reduce the number of human casualties and to minimize material damage in case of disaster. Tsunami waves modeling in laboratory conditions, in contrast to numerical simulation, allows us to obtain more reliable data. In numerical modeling it is impossible to take a large number of random parameters into account (the impact of large-sized debris on buildings and structures during the second and subsequent waves, for example). There are several methods to generate tsunami waves. In our studies, emphasis will be placed on the moving block method and the pneumatic wave generator method. In the moving block method, wave is generated after a solid or loose material collides with a water surface (the tsunami model, whose source is landslide). When using the pneumatic wave generator, a wave or series of waves are formed using a special laboratory installation. The laboratory installation consists of a wave tray or basin in which a tank is installed an open part to the surface of the water. Air from the tank is pumped out by the pump, and the water level in the tank gradually rises. Then with the help of air valves, the water is released and generates a wave. The shape and periodicity of the generated waves can be varied by means of the computer that controls the air valves. The data obtained during the research is necessary both for making corrections in the numerical tsunami models and for designing buildings and structures in tsunami-prone areas.

1. Introduction

According to the set of rules « .1325800.2017 BUILDINGS AND STRUCTURES IN TSUNAMI PRONE REGIONS. Rules of Design and Construction»: tsunami waves are surface gravity waves in the oceans and seas caused by underwater earthquakes and volcanoes, fall of asteroids or other celestial bodies, underwater and above-water coastal landslides, and landslides, as well as underwater explosions of high power. This is a very rare natural disaster, but extremely destructive. In all cases, tsunamis are secondary natural phenomena caused mainly by landslides or underwater earthquakes. It is physically and economically impossible to ensure full protection of the coast from tsunami waves. It is possible only to reduce the negative consequences of the catastrophe.

Historically, tsunami laboratory modeling developed independently of analytical methods of investigation.

Studies of tsunami waves in laboratory conditions, as well as the study of their effects on the coast and coastal structures must meet the criterion of Froude's similarity:

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$$\mathrm{Fr} = \frac{v^2}{gL} \tag{1}$$

V - characteristic scale of speed; L - determining size; g - acceleration of gravity.

2. Numerical models and laboratory methods

One of the most common numerical models used to describe a non-periodic wave is a soliton (single wave) - a surface wave, which consists of a single displacement of the water mass relative to the surface along the vertical. This numerical model of the tsunami wave is most consistent with the moving block method [1]. A single wave is formed after a collision of a solid block or an array of ground [2] moving over an inclined plane with the water surface. The data obtained using the moving block method and the soliton as a numerical model of the tsunami wave, with all their merits, cannot give us reliable results due to many assumptions. The main assumption is that an earthquake produces a series of waves (usually 3-4), rather than a single wave. But when modeling tsunami waves caused by landslides, this method is quite accurate.

To increase the reliability and accuracy, it was proposed to replace a single wave with an N-wave one as a numerical model of a tsunami.

$$\begin{gathered} \eta(x,0) = \alpha H(x - x_2)\operatorname{sech}^2(k(x - x_1)) \\ k = \frac{1}{h}\left(\frac{3H}{4h}\right)^{1/2} \end{gathered} \tag{2}$$

a - scale parameter that allows comparison with single waves; x_1 and x_2 - coordinates of the wave crest and trough; H and h - depth and height of the wave.

The most accurate laboratory method is the generation of a tsunami wave using a pneumatic tsunami generator. For the first time such an installation was applied in the HR Wallingford laboratory in 2008 [3].

3. Foreign experience of conducting experiments in the field of tsunami research

The initial version of the laboratory setup consisted of a wave pool in which a tank was installed, an open part to the surface of the water. The air from the tank was pumped out by a vacuum pump, and the water level in the tank gradually increased. After filling the tank, the water was released and generated a wave. The air valves at the top of the tank, with the help of a special computer, allowed to set the desired shape and frequency of the generated waves. With the help of a pneumatic tsunami generator, sine waves with a period of 50 to 200 seconds, and then solitons and N-waves, were firstly reproduced. In the end, it was possible to simulate a series of waves close in shape to the tsunami waves. (Figure 1)

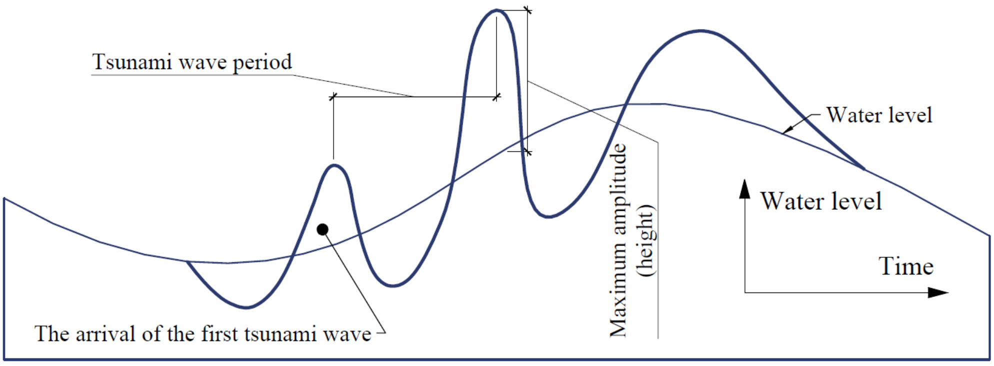

Figure 1. Tsunami trough-led wave structure

Further studies were carried out to calculate the loads and water pressure on the building model, as well as to determine the wave propagation velocity along the coast. In addition, numerical models of the laboratory setup were compiled, which made it possible not only to increase the accuracy of the studies, but also to substantially increase their number.

In 2012, the installation was improved, the tank was installed on a concrete base 0.1 meters' height and the height of the tank cover was 1.9 meters above the surface. Also, 5 sensors were installed to monitor the change in the water surface: 1.2, 3.3, and 5 meters from the tank, and the rest on the pool slope. With the help of valves, it became possible not only to reproduce tsunami waves, but also to form crests (peaks) of these waves.

The main task of the improved laboratory setup was the study of N-waves. The surface of the N-wave formed should firstly deviate below the water level in the basin. The wave crest and the lowest point of the cavity should be approximately symmetrical with respect to the water surface. From the numerical models of the laboratory setup, it was obvious that for the wave crest formation, it would be required to make more manipulations by opening /closing the valve than for a similar point in the wave trough. At the start, the valve was opened at 33 percent, keeping the level in the tank at 1.3 meters. The valve slowly closed until completely closed and held in a fully closed position for several seconds. This manipulation is necessary for the trough-led N-wave formation. Then the valve was opened up to 100 percent to form a wave. Within a few seconds, with a fully open valve, a wave crest was formed, then the valve position was returned to the original 33 percent opening to generate the tail of the wave. At the first stage of the experiment, the closing phase of the valve was approximately 45 seconds, and the opening was 80 seconds. In the subsequent stages of the study, the opening/closing phase of the valve changed to a greater or lesser extent.

4. Tsunami modeling in the Moscow State University of Civil Engineering laboratory

In the framework of the preparation of a methodical manual on the design of buildings and structures in tsunami-prone areas, work on the tsunami waves modeling and the investigation of the tsunami waves effects on the coast and coastal structures can be performed in the laboratory of the Institute for Marine Oil and Gas Production Facilities of the Moscow State University of Marine Engineering [4].

It is also worth noting that as part of the set of rules « .1325800.2017 BUILDINGS AND STRUCTURES IN TSUNAMI PRONE REGIONS. Rules of Design and Construction», there is the following paragraph:

"5.2.5. For hydraulic structures located in tsunami-prone areas, where the value of the vertical splash h_{100} exceeds 4 m, it is necessary to perform physical modeling to clarify the loads. " Here, h_{100} is a splash repeating once every 100 years.

In the same joint venture there is an obligatory Appendix A, in which the characteristic of tsunami hazard of the coastal zones of Russia is given. The main parameter of tsunami hazard is just the value

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of the vertical splash h_{100}. In accordance with the data presented there, the need for physical modeling of the effect of tsunami waves on hydraulic structures occurs during construction in the coastal zone of the Primorsky Territory, the Kamchatka Territory and the Kuril Islands.

The adopted approach corresponds to the analogous norm of set of rules 38.13330.2012, where the physical simulation of the effect of wind waves and swell is mandatory if the height of waves in front of the structure exceeds 5 m.

For experiments it is possible to use a large shallow basin 40x40 meters in size and a depth of about 2 meters (Figure 2), as well as a wave tray whose length is more than 100 meters, a width of about 2 meters and a depth of about 3 meters.

Figure 2. A large shallow pool of the ONIL Marine Oil and Gas Field Hydraulic Structures laboratory of the Moscow State University of Civil Engineering

As a generator of tsunami waves, it is most advisable to use a pneumatic wave generator in a similar design to the installation in the HR Wallingford laboratory.

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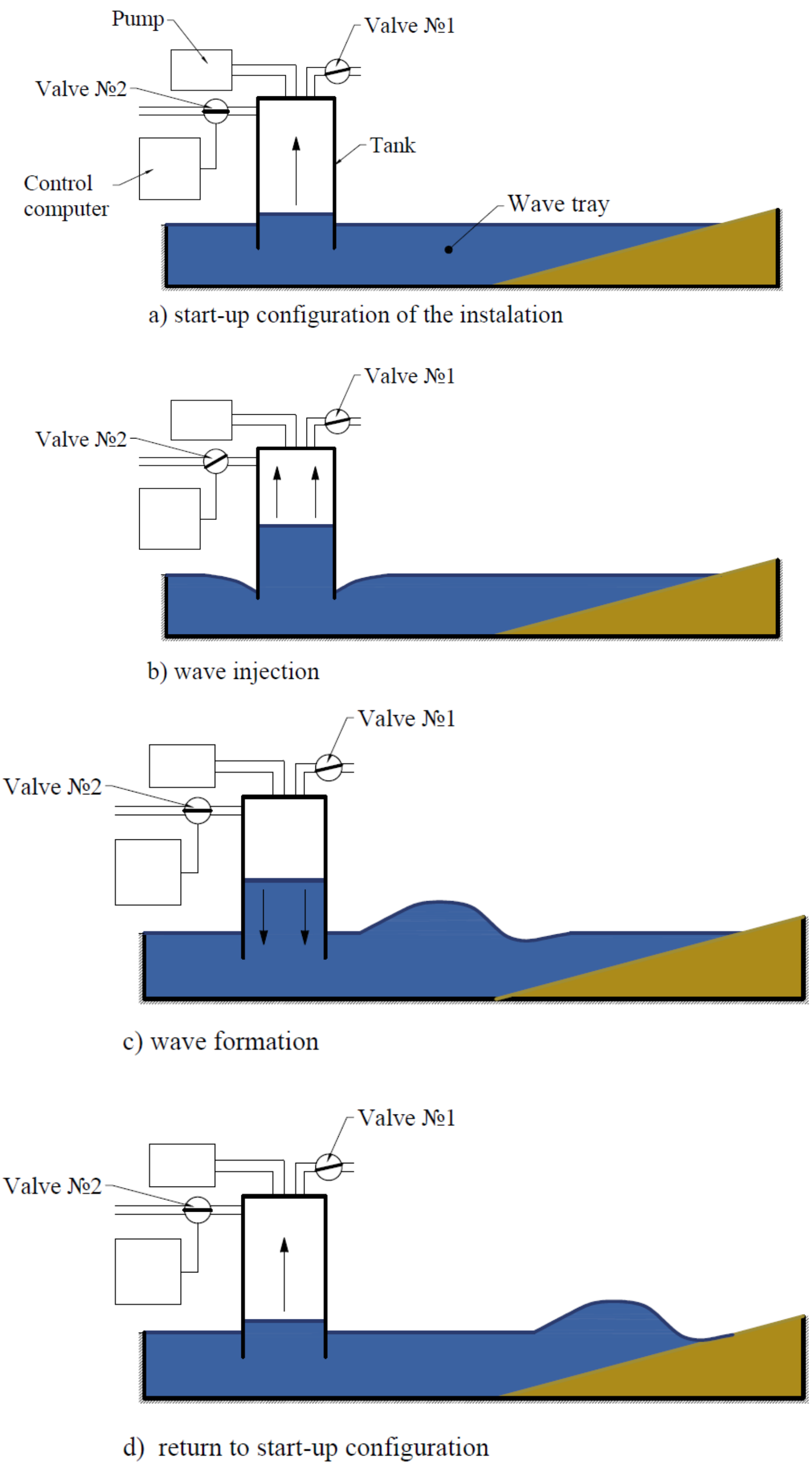

Figure 3. Tsunami waves generation by means of a pneumatic tsunami generator in the HR Wallingford laboratory, steps 1-4; a - the start-up configuration of the installation (step 1); b - water injection into the tank (step 2); c - wave formation (step 3); d - return to start-up configuration (step 4)

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The original purpose of the research is to reliably reproduce a series of tsunami waves (two or three waves). It is also important to choose the scale of the simulation. For example, at a scale of 1:500, the depth of water in the wave product must be 2 meters, the propagation velocity of the disturbance is 4.5 m / s, the period is 54 sec, and the wavelength is 240 meters. At this scale (1:500), to determine the perturbation wavelength, the length of the wave tray is not less than 300 meters.

The impact of the tsunami waves on the shore and on coastal structures is not only the strength of the hydrostatic water pressure and the high-velocity head of the stream. Yes, in real conditions, the first wave usually does not contain malicious objects, namely, various debris (but there may be ships or other marine objects). During the recoil of the first wave, erosion of the bottom soil occurs at the hydraulic structures and washing of the soil from beneath the structures foundations. Subsequent waves already contain a large number of often large-sized debris, which have additional significant impact on the surviving structures. With the recoil of subsequent waves, the processes of erosion and washing out of the soil continue.

An important part of the wave simulation will be the study of the debris impact on the structure, that is, loads from the water flow will also be added by the impact load from the debris. Reliable data on the intensity of these impacts and their orientation can be obtained only from the results of physical modeling. The shape of the coast, the bottom configuration, the strength of the tsunami and the classification and forecast of possible debris for the simulated area are the main variants for research.

In the framework of this global task, it is necessary to solve a number of individual, more narrow, but no less important tasks. For example, how the fragments are transported in the flow, what are the effects of fragments of various shapes, sizes and materials on the hydraulic structure. How does the process of various objects or structures separation from the surface of the earth by tsunami wave take place, etc.

Figure 4. Hydraulic tray with variable gradient

Experiments with the effect of fragments contained in tsunami waves are most expediently carried out in a wave tray in which it is possible to specify the flow characteristics obtained from tests with a pneumatic tsunami generator. Also in such a tray it is possible to change the profile of the shore relatively quickly and add models of various structures.

5. Conclusion

Physical modeling allows us to solve two main tasks. The first is to determine the degree of stability and strength of structures under tsunami impact, and the second is to verify the numerical tsunami models for given conditions.

In the physical modeling of tsunami waves, it is useful to use the experience of physical modeling of wind waves and their interaction with structures. In particular, when comparing the planned picture of waves in the zone of structures obtained in the laboratory and numerical modeling, a comparison should be used, taking into account the vicinity of the control points. Without conducting laboratory studies of tsunami waves, it would be practically impossible to create more or less accurate numerical models. The data that can be obtained during the experiments will be useful not only for the study of tsunamis, but also for floods and mudflows.

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