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HYBRID APPROACH TO MITIGATE TSUNAMI HAZARD ON THE COASTAL AREAS CONTAINING NUCLEAR POWER PLANTS

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Abstract

Nearshore dredging for construction aggregate or beach nourishment can result in a perturbation of natural littoral processes, changes in wave transformation patterns, and a net loss of sand from the littoral system. A hybrid approach is developed which combines methods and results from both traditional Marine Geology and modern Computational Fluid Dynamics (CFD). The model has been successfully applied for solving the issues of environmental security in

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areas of the Black and Azov seas, where the underwater extraction of sand and gravel from the seabed took place. It has been shown that poorly arranged underwater quarry rejuvenate the coast and further development of the coast from young to old age causes terrible washouts in the coastal zone. Calculations performed on the hybrid model, were used to determine the width of the buffer zone for sand deposits. Above hybrid model also was used to obtain an insight on the tsunami hazard on coastal structures. A special interest is related to coastal areas with nuclear power plants (NPP) using ocean water for cooling the reactors. A hypothetical example of the application of the above approach to the events similar to the Fukushima Nuclear Power Plant Catastrophe is under consideration. As a tool for mitigation tsunami hazard on the NPP near shore facilities the method of the “Artificial Bay development” from the two triangle-shaped beach nourishments is proposed. The method provides that part of the tsunami destructive energy performs a useful work for both shore and facilities protection. Generation of tsunami waves by underwater disturbances is investigated.

1. Introduction

In 2004, merciless Tsunamis hit the coasts of India, Sri Lanka, Indonesia, Thailand and other south-east Asian countries [2]. In 2011, the world was awe-stricken by the devastating earthquake in Japan, which was followed by a tsunami on the coast, destruction and leakage of radioactive waste from the Fukushima Nuclear Power Plant (NPP) [1]. This led to the shutdown of the reactor cooling systems and a 20 km population evacuation zone was set. On April 20, 2011 this zone was expanded up to 30 km. The schematic simplified cross-section through one of the reactors at Fukushima is presented. It shows the approximate location of critical component damaged by the tsunami. It was estimated that huge tsunami waves 15 m high run up on the shore. Some of them were 17 meters. In Fukushima the main plant buildings at the top of a slope 10 meters about sea level. Eleven of the twelve emergency generators in service at the time failed. They required water cooling, which was no possible because the tsunami had destroyed the sea water pumps and their motors [1].

One can see the seawater pumps built at a lower elevation 4 m level. Battery units were also flooded. Nuclear power plants are known to require large amounts of water for the reactor cooling process. Hence, it is quite common for a NPP to be located at a close to shore location (about one kilometer away), and this situation is not unique to Fukushima NPP. As an example for a non-Japan placed NPP, one can take Kudankulam Atomic Power Plant in the coastal area of India [2]. Unlike Fukushima, this station was not affected by the tsunami in 2004. However, the risks associated with the existence of a NPP in tsunami-prone coastal areas and the construction of new NPP's still exists. Natural catastrophic events, such as earthquakes and tsunamis, make an incomprehensible impact on the current level of the engineering science.

Nevertheless, in our work, we propose a new hybrid model, the aim of which is to determine the engineering measures to mitigate the effects of these disasters. Some previous considerations are of interest, including the propagation of tsunami waves in the ocean over a random bathymetry and energy transport [16, 5] and some current investigations [10, 11, 12, 23], calculations of tsunami breakwaters [25], rubble breakwaters [4] and a breakwater for coast Sanriku in Japan in 1968 [9].

Investigations of generation and propagation of tsunami waves were conducted over the long time. The principal cause of current state of the problem is an uncertainty of start of underwater earthquakes which are the basic source of tsunami waves. As a result, a corresponding initial boundary value (IBV) problem is also indeterminate [17]. There are another uncertainties, for example, tsunami generation in Southern Asia (December, 2004, 9.3 scales) [8] and repeated earthquakes (March, 2005, 6.3 scales) without tsunami generation. After a catastrophic tsunami in South East Asia in December, 2004 and January, 2005 there was an earthquake in Crimea (near Sudak), as a result of solitary wave propagation in correspondence with a model of earthquake of the wave type [19]. It is based on hydrodynamic streams of a geomaterial along a ray tube of a tectonic current. In this case evolution of the damaged medium is described by the kinetic equation for damage factor. The analysis of the dispersing equation shows that a solution of a problem can be expected for narrow beams of waves in a neighbourhood of critical points of Morse. In a case singular degeneration it leads to discontinuities of structural parameters which can generate earthquake.

Various computing methods and approaches were applied to generalization of the information including the prognosis of earthquakes of the big magnitude in the form of cluster programs [7]. The problem of suppression of tsunami waves is of great importance. According to a recent tsunami in South East Asia together with a great run-up of tsunami waves on coast there were some local sites along a coastal line with a weak run-up. These appearances are similar to focusing and defocusing of wave energy like water wave refraction in a coastal zone [17].

2. Theoretical Background

2.1. Shallow water equations

The model includes a hydrodynamic unit for the tsunami-impacted part of the shoreline. Shallow water equations are written in terms of the water depth $h(x, y, t)$, the bottom $b(x, y)$ and the free surface $h(x, y, t)$:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hu)}{\partial y} = 0, \tag{1}$$

$$\frac{\partial (hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{1}{2} gh^2 \right) + \frac{\partial (huv)}{\partial y} = -\left(g \frac{\partial b}{\partial x} + M \right), \tag{2}$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial}{\partial y}\left(hv^2 + \frac{1}{2} gh^2 \right) = -h\left(g \frac{\partial b}{\partial y} + N \right), \tag{3}$$

where, t is time and x, y are Cartesian coordinates in the horizontal plane, g is acceleration due to gravity, $u(x, y, t)$ and $v(x, y, t)$ are x- and y-components of fluid velocity, respectively, and M and N are the corresponding components of the bottom friction force due to its roughness. Solution to the equations for given boundary and initial conditions by means of the finite-difference method provides data on the parameters of the tsunami waves in the area of interest [8]. Unfortunately, indeterminacy of the setting of the initial boundary value problem for tsunami still is a great problem [11].

2.2. Shoreline evolution equation

This equation was first obtained in work [14], assuming that the sea bed contours are parallel to the coastline. Also the expressions are used which connect the approach angle of deep water waves with the approach angle of the breaking waves:

$$\frac{\partial Q}{\partial x} = -D\frac{\partial y}{\partial t}, \tag{4}$$

$$Q = Q_0 \sin(2\alpha_b), \tag{5}$$

$$\alpha_b = \alpha_0 - \tan^{-1}\left(\frac{\partial y}{\partial x}\right). \tag{6}$$

In the simplest case, the equation of coastal deformation is written in the form of a linear diffusion equation with the diffusion coefficient, which depends on the parameters of waves and sediment

$$\frac{\partial y}{\partial t} = K\frac{\partial^2 y}{\partial x^2}, \tag{7}$$

where the diffusion coefficient is given by: $K = 2Q_0/D$.

More complicated model [3, 6] should include a nonlinear diffusion equation with a number of empirical coefficients depending on the parameters of waves and sediment, as well as a statistical approach to the sea excitement.

2.3. Hydrogeological unit

Hydrogeological unit is built on the basis of stage-theory. It assumes that geological object develops from the “youth” to “old age” under the influence of some driving forces. For example, the Caucasus Mountains are “young” and Ural is “old”. Driving force behind is diversity and different erosion processes. The definition is not just casuistry. Ranking mountains as “old”, may imply the presence of minerals and metals, such as gold etc., bound to fulfillment of some additional conditions.

The aging theory introduces quantification of maturity by a factor. The factor depends on wave parameters and coastal sediments as follows [21, 22, 24]:

$$K = \frac{m - m_0}{m_\infty - m_0}, \tag{8}$$

$$m_\infty = m_0 + 0.37\sqrt{\frac{h_k}{d}B}, \tag{9}$$

$$B = \sqrt[3]{\frac{h_k}{\lambda_k}}, \tag{10}$$

where K, m, m_0, m_∞ are the maturity observed, initial and potential dynamic equilibrium coefficients respectively, h_k, λ_k are the appropriate height and length of the waves in the area of breaking and d is a median diameter of sediments. Those coefficients are determined using the solution of shallow water equations and processing of field and laboratory data. A cross-section of the related wave-tank with experimental set-up is given below in Figure 3.

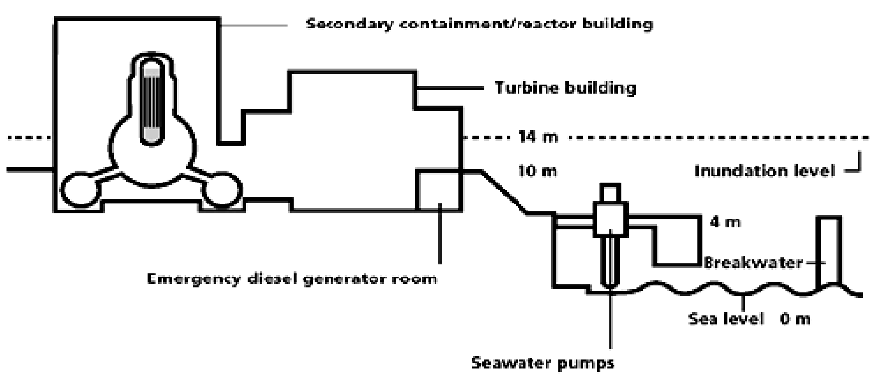

Figure 1. The schematic simplified cross-section through one of the reactors at Fukushima [1].

Figure 2. Nuclear power plant placed on the ocean coast.

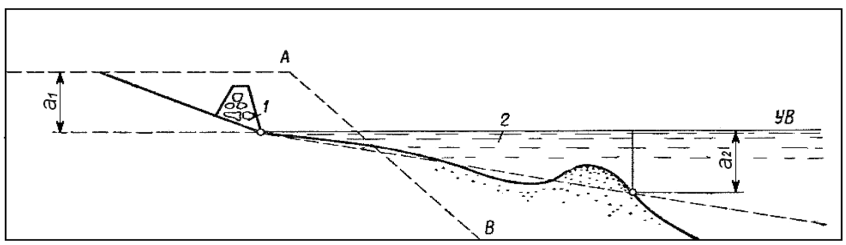

Figure 3. The initial slope of the model, corresponding to the youth stage of the coastal escarpment is schematically noted by the dashed line AB. The stable shape of the coastal escarpment in the stage of maturity is marked by the solid line. The scheme is based on the results obtained in the laboratory for waves with a given height, length and period, produced by the wave-maker [24].

During the performed laboratory experiments [20, 21, 22], it was established that the coastal zone can be considered young if $0 < K < 0.7$. For $K > 1.3$, the shore is old and stable. The transition between old and young mode of coastal zone corresponds to the values in the interval $0.7 < K < 1.3$.

3. Results and Discussion

3.1. Applications to underwater careers

The hybrid model has been successfully applied for solving the issues of environmental security in areas of the Black and Azov seas, where the underwater extraction of sand and gravel from the seabed took place. It has been shown that poorly arranged underwater quarry rejuvenates the coast and further development of the coast from young to old age causes terrible washouts in the coastal zone. Calculations performed on the hybrid model, were used to determine the width of the buffer zone for sand deposits.

3.2. Applications to tsunami

A hybrid model is also used in connection with the problem of mitigating the devastating impact of the tsunami waves on a straight section of the coast, near which a NPP, that uses sea water for cooling the reactors, is located. The first stage uses of the shallow water on the assumption that the time, place and the parameters of the initial perturbation of the surface water from quake are known and initial boundary value problem for the shallow water equations can be applied [13]. An example of the numerical solutions to the problem of propagation of tsunami waves from the perturbations of the free surface of the liquid is shown in Figure 4.

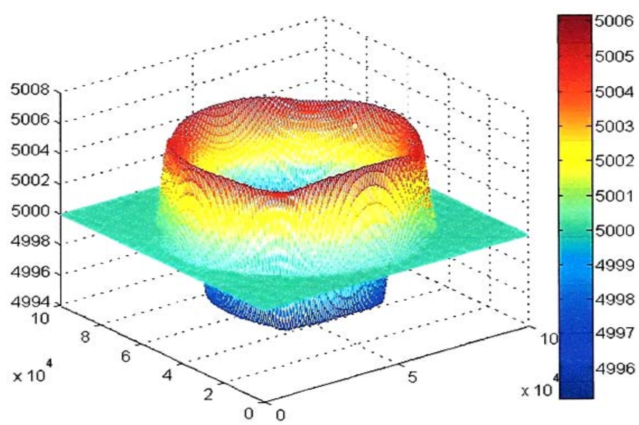

Figure 4. An example of the tsunami wave obtained by means of the numerical solution of the shallow water equations.

The numerical simulations data can be used to estimate approximately the parameters of the tsunami at its exit to the zone of breaking waves. In the second stage, these data are used with the data from the hydrogeological block. In the third phase, the numerical solution of the evolutionary equation for the coast line takes into account especially the specifics of hydrodynamics and sediment lithodynamics of the coastal zone on site. In this, part of the tsunami energy is used for the shore and NPP protection. This process is illustrated by enclosed Figure 5. With relation to this figure consider a part of the hypothetical beachfront confined by two groins, where some facilities of the nuclear power plant are placed.

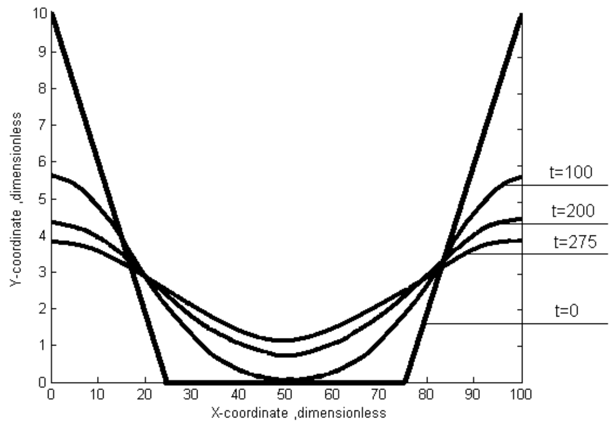

Figure 5. Development of the artificial bay for mitigating tsunami impact on the near-shore nuclear power plant facilities for different times.

3.3. Nonlinear wave propagation over inhomogeneous moving bottom

The original problem of nonlinear water wave propagation over inhomogeneous moving bottom is stated for the velocity potential $\varphi(x,\ y,\ z,\ t)$ is of the form [18],

$$\beta\nabla^2\varphi + \varphi_z = 0 \text{ on } \Omega, \tag{11}$$

$$\Omega = \{(x,\ y,\ z) : -\infty < x,\ y < \infty,\ z \in [0,\ -h_0]\},$$

$$\eta_t + \alpha\vec{\nabla}\varphi \cdot \vec{\nabla}\eta = \frac{1}{\beta}\varphi_z \text{ at } z = \alpha\eta, \tag{12}$$

$$\eta + \varphi_t + \frac{\alpha}{2\beta}\varphi_z^2 + \frac{\alpha}{2}(\vec{\nabla}\varphi)^2 = 0 \text{ at } z = \alpha\eta, \tag{13}$$

$$\gamma(\xi_t + \alpha\vec{\nabla}\varphi\cdot\vec{\nabla}\xi) - \alpha\vec{\nabla}\varphi\cdot\vec{\nabla}h_0 = \frac{\alpha}{\beta}\varphi_z$$

$$\text{at } z = -h_0(x, y) + \gamma\xi(x, y, t), \tag{14}$$

where ∇^2 and $\vec{\nabla}$ are horizontal operators, η is surface elevation, h_0 is water depth; ξ is a disturbed bottom surface. The problem is characterized by the values: $\beta = (h_0/l)^2$ is the dispersion parameter, $\alpha = a/h_0$ is the nonlinearity parameter, $\gamma = \xi_0/h_0$ is the parameter of non-stationary state of the bottom.

In (10)-(14), non-dimensional values are used according to

$$(x^*, y^*) = (x, y)/l, \quad (z^*, h_0^*) = (z, h_0)/h_0, \quad \xi^* = \xi/\xi_0,$$

$$\varphi^* = \varphi\sqrt{gh_0}/gl, \quad t^* = t\sqrt{gh_0}/l, \tag{15}$$

where l and h_0 are the characteristic length and depth, and ξ_0 are the amplitudes of free surface and bottom elevations, respectively.

On the basis of (11)-(14) the evolution equations for propagation of weak nonlinear-dispersive water waves are derived. Assumptions of the theory of long wavelength are introduced.

The problem (11)-(14) taking into account (15) with exactness up to order $O(\alpha, \beta, \gamma)$ after cumbersome can be reduced to the following evolution equations:

$$\frac{\partial^2\varphi_0}{\partial t^2} - c_0^2(\eta, \xi)\nabla^2\varphi_0 - \frac{\beta}{2}\frac{\partial^2\nabla^2\varphi_0}{\partial t^2} + \frac{\beta}{6}\nabla^4\varphi_0 = \frac{\partial F}{\partial t}, \tag{16}$$

$$F = -\xi - \beta\frac{\partial^2\xi}{\partial t^2} + \frac{\beta}{2}\nabla^2\xi, \tag{17}$$

$$\eta_0 = -\frac{\partial\varphi_0}{\partial t}, \quad c_0^2(\eta, \xi) = 1 + \alpha\eta_0 - \gamma\xi. \tag{18}$$

In linear case, $\alpha \to 0$ and without the dispersion, $\beta \to 0$ the system (14), (15) is reduced to the equation as

$$\vec{\nabla} \cdot (h_0 \vec{\nabla} \eta_0) - \frac{\partial^2 \eta_0}{\partial t^2} = -\frac{\partial^2 \xi}{\partial t^2}. \tag{19}$$

Equations (16)-(19) can be used to investigate water wave propagation over an inhomogeneous excitable bottom. At the same time, the exact statement of corresponding initial boundary problem on the basis of (16)-(19) is directly connected with no determination of triggering mechanism of the underwater earthquake, as the main source of tsunami wave generation.

The corresponding linearized initial boundary value problem for tsunami wave generation by a local elevation on the basis of (11)-(14) is investigated. The problem is solved by using the Hankel integral transform in a radial coordinate and the Laplace integral time transform accompanied by numerical inversion. Numerical results for axisymmetric horizontal bottom disturbance (underwater earthquake) are analyzed. The results of calculations demonstrate that increasing velocity of the bottom excitation in time $t_0 = 0.3, 0.6, 0.9$ and the velocity of its decay $\alpha = 1.5, 2.5, 3.5$ can lead to essentially increasing heights of the free-surface (Figures 6 and 7).

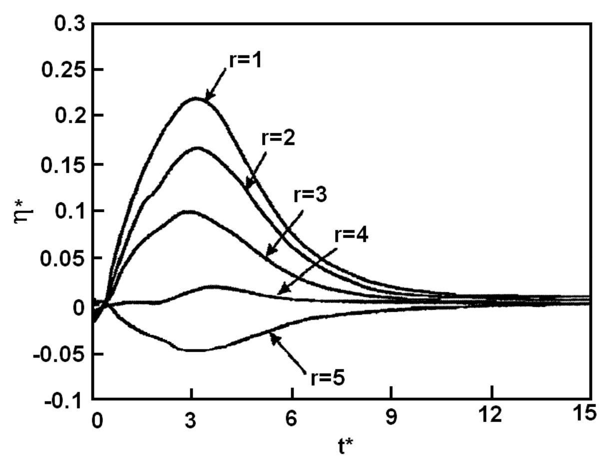

Figure 6. Free surface elevations η^* at different distances from the epicenter r^* for $t^* = 0.6$, $\alpha = 2.5$, $\xi^* = 1.0$.

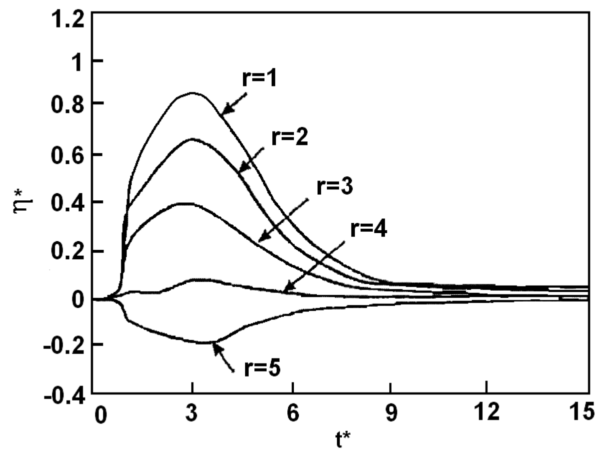

Figure 7. Free surface elevations at different distances from the epicenter for $t^* = 0.9$, $\alpha = 3.5$, $\xi^* = 1.0$.

Summary

1. A new approach is developed which combines methods and results from both traditional Marine Geology and modern Computational Fluid Dynamics (CFD) to obtain an insight on the tsunami hazard on coastal structures.

2. A hypothetical example of the application of the above approach to the events similar to the Fukushima Nuclear Power Plant Catastrophe is under consideration.

3. As a tool for mitigation tsunami hazard on the NPP near shore facilities the method of the “Artificial Bay development” from the two triangle-shaped beach nourishments is proposed. The method provides that part of the tsunami destructive energy performs a useful work for shore and facilities protection.

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