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QUESTIONS OF TECHNIQUE OF LABORATORY WAVE STUDIES IN PORT WATER AREAS ENCLOSED BY PROTECTIVE STRUCTURES

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In determining the wave regime in the water areas of ports with different directions and parameters of the initial waves special attention must be devoted to questions concerning the technique used in laboratory studies on large-scale spatial models in order to obtain trustworthy and reliable results.

Keywords: wave investigations; similitude phenomena; modeling criteria; modeling scales.

The design, construction, and rehabilitation of sea ports, which are practically always unique and expensive facilities, are maintained by appropriate scientific support. The program of this support includes modeling of the wave processes in the port water areas. It should be noted that the relative significance of mathematical modeling is growing today. However, the role of investigations carried out on hydraulic models under laboratory conditions remains significant and will continue to be significant in view of the sharply varying topography of the floor of bodies of water in sea ports, the complex configuration of hydraulic structures and their construction, as well as in other cases. In such situations complex flow and surge systems arise which already function together in sections of the coastal zone. In many cases the emergence of these types of systems and their effects cannot be predicted by means of analytic methods. Laboratory investigations on large-scale spatial models are performed in order to determine the wave regime in the water areas of ports with different directions and parameters of the initial waves in light of diffraction, refraction, and reflection of waves.

It is necessary to assure similitude of phenomena when modeling wave processes in both planar and spatial models. Phenomena are referred to as similar when the characteristics of one phenomenon may be obtained from a second phenomenon by conversion of the characteristics of this phenomenon by means of the constants of relationships as is done in a transition from one system of units of measurement to another.

Two basic requirements must be satisfied to assure the similitude of phenomena:

Mechanical similitude includes:

— geometric similitude — when the distance between corresponding points of the model and in Nature are in the same relationship;

— kinematic similitude — when the velocities of the particles and the accelerations at all similar points are proportional and identically directed relative to the boundaries of the flow, i.e., the trajectories of the particles must be geometrically similar;

— dynamic similitude — when parallelism and proportionality of forces acting at similar points in the model and in Nature, as well as constancy of the relationship between the masses of any two similar points are the basic features of dynamic similitude.

Uniqueness conditions by means of which the boundary and initial conditions in the solution of differential equations are uniquely determined (uniqueness of a solution is assured).

In the general case simulation of hydrodynamic phenomena requires simultaneous observance of four similitude criteria, which is also fully taken into account in modeling of wave processes in both planar and spatial models [1 – 3].

I. Strouhal homochrony criterion (H_{h}) (Strouhal number) (Sh)

$$H_{\mathrm{h}} = \mathrm{Sh} = \frac{ut}{l} \tag{1}$$

characterizes the inertial forces that arise in nonsteady motion of a fluid, in particular, in wave motion. Under the conditions of stationary (steady) flows the criterion Sh = 0.

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II. Froude's criterion

$$\mathrm{Fr} = \frac{\upsilon^2}{gl} \quad (2)$$

characterizes the effect of the forces of gravity (volumetric or mass forces), more precisely, the ratio of the inertial forces to the gravitational forces.

III. Reynold's criterion

$$\mathrm{Re} = \upsilon l/\nu \quad (3)$$

characterizes the effect of viscosity forces (forces of internal friction) or ratio of the force of inertia to the viscosity force.

IV. Euler's criterion

$$\mathrm{Eu} = \frac{P}{\rho\upsilon^2} \quad (4)$$

characterizes the forces of pressure in a fluid, or ratio of the force of pressure to the force of inertia.

Here l is the characteristic dimension (depth of water, dimension of obstacle, support, etc.); υ — characteristic velocity (of flow, orbital velocity of particles in a wave, etc.); t — time (peroid of wave); ν — coefficient of kinematic viscosity; and P — pressure of fluid.

The above criteria characterize phenomena where the effects of the forces of capillary (surface) tension may be ignored. Lamb's recommendations [4] must be used where it is necessary to estimate the influence of the forces of surface tension. According to Lamb, the minimal length of surface waves $\lambda_{\min} = 1.73$ cm, while the rate of propagation of surface waves $c = 23.2$ cm/sec. These waves are capillary waves. Compatible waves, whether gravitational or capillary waves, may exist at rates of propagation of the waves greater than 23.2 cm/sec.

The rate of propagation of surface waves is given as

$$c = \sqrt{\frac{gl}{2\pi} + \frac{2\pi T' g}{\gamma\lambda}}, \quad (5)$$

where g is the acceleration of gravity; λ — wavelength; T' — surface tension equal to 0.074 g/cm at 20°; and γ — bulk density of water.

As the wavelength grows, the first term in the radicand of (5) bccomes dominant and the influence of the second term drops, i.e., waves that are initially capillary turn into gravitational waves. The influence of the forces of surface tension will not exceed 5% in the case of a rate of propagation of the combined waves of 30 cm/sec. At $c = 50$ cm/sec the influence of the forces of surface tension is practically absent.

Accordingly, it may be established that the waves in the model should be of length greater than 170 mm and height greater than 10 mm in order to eliminate the influence of the forces of surface tension. In this case the influence of Weber's criterion $\mathrm{We} = \sigma/(\rho\upsilon) = 0$ (which governs the similitude principally of capillary forces) cannot be taken into account, assuming that modeling of the waves is performed on the basis of Froude's law.

To exclude the influence of the forces of surface tension, the vertical scale of the model must not be less than 1:100 – 1:150.

In modeling wave processes in port water areas the forces of gravity and inertia are the basic effective forces. Thus, simulation must be performed on the basis of Froude's criterion (Fr). In this case Strouhal's criterion (Sh) is fulfilled automatically.

The scale of the simulation is selected so that the values of Reynold's criterion (Re) are located in what is known as the self-similarity zone of this minor criterion.

On the basis of numerous studies [2, 3, 5] it has been established that the lower boundary of the self-similarity zone for spatial models is defined by the Reynolds number $\mathrm{Re}_{\mathrm{self}} \geq 2000$ at which a turbulent surge regime is achieved.

The condition $\mathrm{Re}_{\mathrm{self}} \geq 2000$ is generally not observed at scales of simulation less than 1:100 – 1:200. In this case it is best to attempt to create a distorted model of a port in which the vertical scale of the model is made larger than the horizontal scale. In the course of laboratory investigations of port water areas simulation distortion of the scales over a rather broad range as a function of the particular problems confronting the researcher was applied, with distortion of the horizontal scales from 1:40 up to 1:500 and even up to 1:1000 and distortion of the vertical scales from 1.5- to 2.5-fold and rarely up to 10 times greater. For example, in a study of the ports of Los Angeles and Long Beach a hydraulic model with 1:400 horizontal scale and 1:100 vertical scale was constructed. This model was the largest in the United States and occupied an area of 4068 m^2.

In a distorted model the planned contour of the port water area and port structures is realized in a horizontal scale with the vertical elements of the structure created on a scale that is larger than the horizontal scale. The ratio of the vertical to the horizontal scale is referred to as the distortion coefficient k_{dist}. Surges in the model, both the initial surges outside the port water area as well as those extending throughout the port water area are modeled in the vertical scale. It should be noted here that until recently there were no sufficiently well-based values of the distortion coefficients k_{dist} for use in spatial models.

The depth of the turbulent layer of water in a wave flow must be estimated analytically in order to determine the value of k_{dist}.

An expression for the Reynolds number Re for a water level equal to z in monochromatic-type waves has the form

$$\mathrm{Re} = \frac{2r_z v_z}{\nu}, \quad (6)$$

where $r_z = h/2 \times \exp(-2\pi z/\lambda)$ is the radius of the orbit and $v_z = 2\pi r_z/T$ is the orbital velocity.

After some algebraic transformations we obtain the following expression for the turbulent layer z:

$$z = \frac{\lambda}{2\pi} \ln \frac{\pi h^2}{\mathrm{Re} T \nu}. \qquad (7)$$

The turbulent layer of water with Reynolds number $\mathrm{Re} = 2000$ proves to be equal to $2.5h$ [6, 7]. Most of the energy of the wave (around 90%) is concentrated in a zone of the surface layer of water $3h$ in width Experimental data exhibit lesser values (around $2h$) [6].

These features of a wave flow show that in the flow the turbulent layer is concentrated in an upper zone around three wave heights in width. This circumstance may serve as an experimental and theoretical base of evaluation for studying the wave regimes of a port water area in distorted models of ports.

However, to obtain more precise values of k_{dist} a large-scale series of trials was carried out on a small section of a port water area with varying depths for different distortion coefficients. The value of k_{dist} was set equal to 1.5, 2.0, 2.5, and 3.0 [3].

The series of trials was performed in the wave basin of the Moscow State University of Civil Engineering branch laboratory on rigid nonerodable models. In each model the trials were performed with different designs of protective structures.

As a result of the investigations it should be noted that in order to obtain reliable experimental data in modeling the value of the distortion coefficient k_{dist} must not exceed 2.5.

In order to correctly realize wave surges corresponding to given parameters in a distorted model of, it is necessary to maintain a wave slope h/λ and a relative water depth d/λ similar to natural conditions, i.e., with distortion of the model these conditions lead to reproduction of the wavelength λ, the height h, and period T in the vertical scale.

If structures with inclined profile are planned for a port water area, the construction of the distorted model must retain the same steepness of the slopes of the structures and shores that are found in Nature. Otherwise, in the distorted profile the slopes may prove to be steeper in the distorted model, which will lead to an increase in the reflection of waves and, thereby, to overstatement of the characteristics of the wave surges in the body of water. In order to decrease this error it is recommended that the steepness of the slopes in the model should be made the same as in Nature above the water level and below the water level down to a depth of $2.5h$. Below this depth the slope in the model may be made steep (right up to the vertical), since oscillatory motion in this zone is already insignificant and cannot exert a substantial effect on the wave regime in the port water area, thus assuring a sufficient volume of water in the model within the limits of the port water area. In conclusion, it should be noted that in domestic studies of wave surging in the water areas of outer harbors and of ports, distortion of the scale with distortion coefficient from 1.5 to 2.0 is used.

In the case of very significant dimensions of a body of water simulation must be performed in a sufficiently fine scale of 1:500 – 1:750, which leads to the need to create waves of extremely low height and extremely low length. In turn, this leads to the need to compute the forces of surface tension and the friction and viscosity forces. Moreover, the water depth in the model must also not be so low that there are significant losses of wave energy due to friction about the surface of the model that leads to underestatement of the modeled heights of the waves. Thus, in order to obtain reliable experimental data it is often necessary to adopt solutions that involve a comparatively small section of the port water area in the region of the studied structures on a scale not less than 1:100 – 1:150 with distortion coefficient not greater than 2. Finally, the modeling scales (both the horizontal and the vertical scale) is made the maximally possible.

Where there are protective structures present, it is necessary to discuss modeling of the width of the entrance to the protected body of water. To assure the most correct development of wave diffraction in a distorted model the width of the entrance in the model should not be less than the length of the modeled wave λ. It remains unclear how to develop diffraction of waves if the width of the entrance is less than the length of the modeled wave ($B \leq \lambda$). Thus, an additional series of trials was conducted in the wave basin of the Moscow State University of Civil Engineering branch laboratory on a rigid nonerodable model of a port protected by converging breakwaters in order to determine the permissible errors that may arise in experiments when performing investigations where the entrance is of limited width ($B \leq \lambda$). A model of a port protected by converging breakwaters is presented in Fig. 1.

The influence of the width of the entrance into a port on the wave parameters of a protected water area with different directions of approach of the waves and different intensities of the wave action was determined in the course of carrying out the experimental investigations. The width of the entrance was varied in the range $B = (0.5 \ldots 3)\lambda$, where λ is the wavelength. The dimensionless residual wave coefficient obtained at a series of measurement points was determined from the formula $K = h_i/h_{\text{init}}$, where h_i is the height of the wave at a given point of the port water area and hinit the height of the wave at the entrance to the port.

Graphs of the dependences of the residual wave coefficient on the relative width of the entrance were constructed from data obtained as a result of data processing with the relative distance r/λ varying from 1.0 to 5.0 and the angles $\varphi_1 = \varphi_2 = 90°$ (angles between axis of breakwaters and boundaries of the wave shadow).

From an analysis of these dependences we were led to the following conclusions:

— with a width of the entrance $B/\lambda \geq 1.5$ no substantial variation in wave surging was established (the wave parameters remained constant);

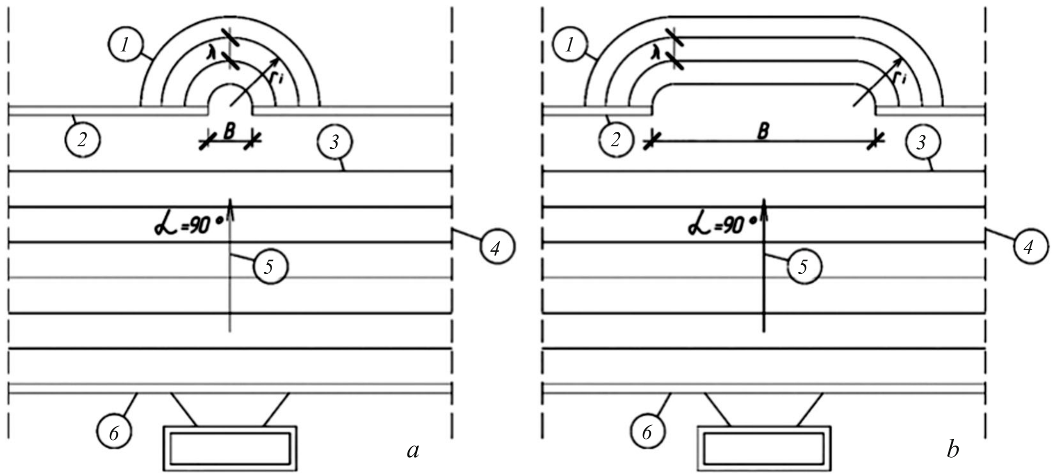

Fig. 1. Model of port protected by converging breakwaters: *a*, $B < \lambda$; *b*, B λ; *1*, front of diffracted waves; *2*, converging breakwaters; *3*, front of initial waves; *4*, walls of wave channel; *5*, initial wave line; *6*, wave generator.

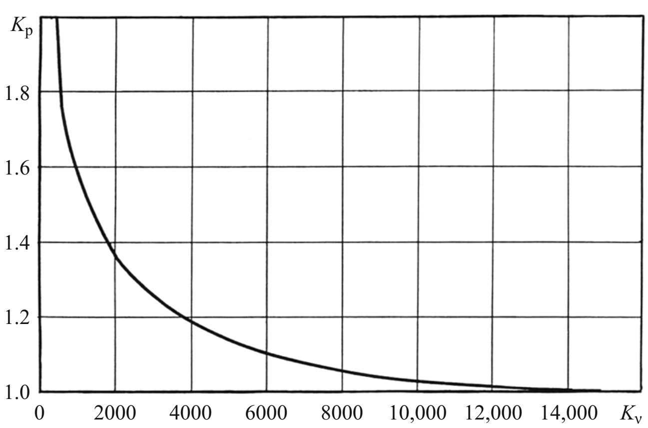

Fig. 2. Graph of scale coefficients that take into account the influence of the viscosity of water on the wave height under laboratory conditions.

TABLE 1. Values of Correction Factors of Influence Coefficient kinfl in the Case of Convergent Breakwaters

Relative width of entrance B/λ	Relative distance r/λ	Influence coefficient k_{infl}
1.0	1	1.00
	3	1.02
	5	1.04
0.75	1	1.10
	3	1.15
	5	1.20
0.5	1	1.20
	3	1.25
	5	1.45

— with a width of the entrance $B/\lambda < 1.5$ the heights of the waves in a protected body of water decrease;

— where the heights of the waves in a protected body of water vary, when the width of the entrance $B < 1.5\lambda$ a correction factor for the influence k_{infl} should be introduced; the values of the correction factor are presented in Table 1.

Analogous investigations were carried out in a body of water protected by a single breakwater. In this case the minimal width between the lead breakwater and the wall of the wave channel was determined. The results are presented in Table 2.

In modeling performed in Froude's approach with modeling scales 1:200 and less it becomes necessary to estimate the influence of the viscosity forces and forces of surface tension. The recommendations of A. S. Ofitserov are usually used to estimate the influence of viscosity forces. Here correction factors $k_n = f(k_\nu)$ as represented in Fig. 2, where k_ν constitutes the Reynold's criterion [2], are introduced on the basis of a generalization of experimental data:

$$k_\nu = \frac{\upsilon_{\max} h}{\nu} = \alpha h^2, \tag{8}$$

where

$$\alpha = \frac{1}{2v}\sqrt{2\pi g}\sqrt{\frac{1}{\lambda}\coth\frac{2\pi d}{\lambda}}, \tag{9}$$

It is evident from the graph that the case characterized by the value $k_\nu = 15{,}000$ (for which $k_n = 1.0$) is adopted for the case of natural conditions, which of course is conditional.

TABLE 2. Values of Correction Factors of Influence Coefficients k_{infl} in Case of a Single Breakwater

Relative width of entrance B/λ	3.0			2.0			1.0		
Relative distance r/λ	1	3	5	1	3	5	1	3	5
Influence coefficient k_{infl}	1.0	1.0	1.04	1.0	1.03	1.1	1.02	1.08	1.18

TABLE 3. Values of Correction Factors in Response to the Viscosity Forces of Water (I. A. Vaisfel'd)

h, cm	0.5	1	1.5	2	3	4
k_v	140	560	1250	2250	5000	8900
k_{corr}	1.5	1.19	1.07	1.01	1	1

TABLE 4. Values of Correction Factors for the Effect of the Viscosity Forces of the Water (A. S. Ofitserov)

h, cm	0.5	1	1.5	2	3	4
k_v	140	560	1250	2250	5000	8900
k_{corr}	2.3	1.87	1.55	1.32	1.12	1.04

It should be noted that the recommendations of different researchers in estimation of the viscosity forces are highly contradictory. For example, the correction factors proposed by A. S. Ofitserov and I. A. Vaisfel'd with the same initial values differ up to 1.5-fold and more (Tables 3 and 4).

Besides the recommendations of by A. S. Ofitserov and I. A. Vaisfel'd, whose recommended values of the correction factors significantly diverge, the following formula proposed by G. Lamb [4] may also be used to estimate the influence of the viscosity forces on damping of wave surges throughout a model:

$$t = 0.712\lambda^2, \tag{10}$$

where t is the length of time it takes to completely dampen a wave, sec, and λ the wavelength, cm.

Let us next estimate the possible loss of the design wave height as a consequence of not taking sufficient account of the viscosity forces. As an example, we use the minimal design wave parameters in the model (on a 1:75 scale) $h = 3.86$ cm and $\lambda = 49$ cm ($\lambda = \lambda_d \tanh k_d$).

The rate of propagation of waves at a finite depth C was determined from formula (5). The rate of propagation of a group of waves, or group rate, was calculated in the model from the dependence

$$U = \frac{1}{2}C\left(1 + \frac{4\pi d}{2kdl\mathrm{Sh}}\right). \tag{11}$$

Total damping of a wave occurs once it has it traversed the distance

$$C = Ut \approx 0.9 \text{ km}. \tag{12}$$

The slope of a wave surface is given as

$$J = 0.5h/S = 2.14 \times 10^{-5},$$

i.e., 21.4 mm per 1 km.

The decrease in the height of a wave along the length of the model amounts to $\Delta h = 0.15$ mm or roughly 0.39% of the wave height (if it is recalled that $h = 3.86$ cm, or 38.6 mm). Hence, it is evident that ignoring the viscosity forces leads to an error that lies significantly below the limits of measurement precision, moreover in the direction of understating the design height of a wave.

CONCLUSIONS

1. The methods of calculating the diffraction of waves that are presented in existing regulatory documents may be used only in relatively simple cases where the water areas of the port are protected by a single breakwater, groin, or by convergent breakwaters. With the use of these methods it is possible to calculate the wave parameters in the case of constant water depth in the body of water, disregard the influence of refraction and of losses of energy as a result of friction against the floor, but these methods do not enable us to take into account the variation in the water depth or repeated reflection of waves by the inner port walls and moorages.

2. It should be noted that when investigations are performed on hydraulic models with the use of the above recommendations it becomes possible to take into account variable factors and skillfully create compact protective structures with minimal capital investment. This affects the quality, simplicity, and reliability of the operation of the structures as well as the effectiveness with which construction materials are used.

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