Contributions to the Establishment of the Static and Dynamic Interaction Mechanism between Water and Hydro-structures

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ABSTRACT

Contents

Key Words: Hydro-structure; Wind, current and wave forces; Simulation; FLUENT; Water level velocity; Potential vector.

In the present paper we refer especially to the hydrostatic and hydrodynamic action of the water on the inland water structures.

The main objectives of the thesis are:
- simulation of the external forces action – wind, current, waves – on the brake-waters;
- the use of FLUENT simulator as experimental stand;

- establishment of pressure gradient if the flow has a linear variation with application in the determination of level variation of the liquid in the lock chamber.

To accomplish the main objectives, we had the secondary ones:

- synthesis of forces acting on the hydro-structures: brake-waters, channels, barrages, locks;
- flow model through a broken break-water (barrage);
- analytic determination of the flow for a constant velocity of the water level in the lock chamber.

In the first chapter we made some considerations regarding the history of the hydro-constructions, their contributions to the development of the mankind. It is emphasized the importance of the knowledge of natural waters characteristics in the study of the hydro-structures. In the chapter is presented the hydro-graphic basins, the river flow characteristics, important notions for our study.

Chapter 2 is dedicated to the study methods for the water action on the hydro-structures: infinitesimal method, dimensional analysis method, average value and experimental coefficients methods, analogies methods, similarity method, statistic method and computer fluid dynamics method. In this context, we mentioned the methods utilized in our research.

A study of the inland channels was presented in the Chapter 3. We made the accent on the Danube-Black Sea Channel, on the model experimentation before the project. This study allows us to compare the results of mathematical approach with the physical reality in the zone of Cernavoda lock.

In the Chapter 4 we try a complete presentation of the forces acting on the hydro-structures, necessary to realize a good mathematical model. We presented the wind forces, the current forces and the wave forces. We also describe the hydrodynamic interaction forces: Ship-Bottom, Ship to Wall and Ship to Ledge, Ship to Wall and Ship to Bottom in the Channels. Collision with Ship is a force with mechanical origin.

The action of the forces on the hydro-structures is the subject of the Chapter 5. This chapter begins with the presentation of Computer Fluid Dynamics (CFD) method – FLUENT. FLUENT is a programme based on the numerical calculation of the finite volume. The general equation of the mass, momentum and energy conservation is:

$$\frac{\partial}{\partial t}\int_V \rho\Phi dV + \oint_A \rho\Phi V dA = \oint_A \Gamma\nabla\Phi dA + \int_V S_\Phi dV \,, \qquad (1)$$

where the first term refers to the unsteady flow, the second to the convection, the third to the diffusion, etc. If $\Phi = 1$ we have the equation of continuity. If $\Phi = h$ we have the equation of energy.

To make the calculation it was necessary to built, in other programme, GAMBIT, the geometry of the break-water and to create the mesh (volumes in 3D or surfaces in 2D).

On the break-waters act the force of wind, less important then other forces, the force of current and, especially on the marine brake-waters the wave forces. The problem of the current action becomes more serious if we discuses about the great velocities, as the high flood on the rivers.

In the paper we propose to use the FLUENT program as experimental stand. Why do we do this? It is often difficult and expensive to achieve a model. It is also difficult to calculate the phenomena in the nature scale using the FLUENT. So we calculated the physical parameters, using FLUENT on the model and we passed them, using the similitude criteria, in the nature. We illustrated the method with a spectacular example: the flow through a broken barrage.

First, we established the model law, taking into account the physical magnitudes which influence the analyzed phenomena. Afterwards we calculated the scales of these physical magnitudes for normal similitude (a single geometrical scale). Using FLUENT we determined the values of the velocity and forces acting on the barrage (the unbroken part). Finally, we passed the "experimental" data in the nature by application of scale for physical magnitudes.

We presumed an experiment on the scale 1:25 (k_l = 25) of the flow through a broken barrage:

- symmetrical brakewaters left L = 25 m; l = 2,5 m, h = 12,5 m;
- length of the breach d = 250 m;
- water velocity v = 10 m/s.

By applying Froude similitude, it results:

$$\frac{v^2}{gl} = \frac{v'^2}{g'l'} \quad \text{(we noted with ‘ the model magnitudes).} \qquad (2)$$

Knowing that g = g', it results th scale of velocity: $k_v = \sqrt{k_l} = 5$.

The scale of the forces can be established using the formula $F = \gamma V$, where γ is the specific gravity of the fluid. Having the same fluid – water – in the nature and on the model, we can write:

$$k_F = k_l^3. \qquad (3)$$

So v’ = 2 m/s. The dimensions of symmetrical break-waters on the model: L’ = 1 m; l’ = 0,1 m; h’ = 0,5 m. Length of the breach d’ = 10 m.

The solving of the problem is based on pressure notion, implicit formulation. We can notice that we work in 3D, symmetry conditions do not allow to use 2D. We consider the general case of unsteady movement: $\bar{v} = \bar{v}(\bar{r}, t)$. Very important: we consider the biphasic flow,with free surface.

The force acting on model brakewater is 1 714 N. The scale of the force is $k_F = k_l^3$. So the force acting on the remaining break-water is:

F = 1714 x 25^3 = 26 781 250 N = 2 678*10^3 daN.

We consider the case of a break-water designated to protect the harbor area, situated perpendicularly on the current velocity direction of a river.

The dimensions of the underwater part are: L = 200 m; l = 2,5 m; h = 12,5 m.

The velocity of the water current: v = 2 m/s.

The model, built at the scale 1:25, will have the dimensions:

L’ = 8 m; l’ = 0.1 m; h’ = 0.5 m.

By applying Froude similitude we’ll obtain v’ = 0.4 m/s.

To solve the problem, using FLUENT programme, we‘ll make the conditions:

- implicit formulation;
- 3 D;
- unsteady movement;
- turbulence model: k-omega.

We’ll consider the biphasic flow, with free surface and with contact between air and water. The calculation begins from an entrance velocity, Ox positive direction: v’ = 0.4 m/s.

After calculation we obtained the force acting on the model break-water: 8681 N.

To calculate the force in the nature, we apply the relation (3):

F = F’ x k_F = 8681 x 25 x 25 x 25 = 135 660 625 N = 13 566 x 10^3 daN.

Some problems, especially related to the long objects (conduit, break-waters, etc.) can be solved using two geometrical scales (one for length and one, smaller, for diameter). By applying the formulas for distortional similitude, we can pass from the model to the nature.

Now we’ll built a model at two scales as follows:

$$k_x = k_z = 25; k_y = 200. \qquad (4)$$

The distorsional rate wi’ll be:

$$k_1 = \frac{k_y}{k_x} = 8. \qquad (5)$$

The model, built at two scales, will have the dimensions:
L’ = 1 m; l’ = 0.1 m; h’ = 0.5 m.
By applying Froude similitude (2) we’ll obtain also v’ = 0.4 m/s.
In this case the force scale will be:

$$F = \gamma V \Rightarrow k_F = k_\gamma k_x^2 k_y \qquad (6)$$

and taking into account that $k_\gamma = 1$, it results:

$$k_F = k_x^2 k_y . \qquad (7)$$

Using FLUENT programme we calculated the force acting on the distortional break-water model: 1207 N.

To obtain the force acting on the real break-water we apply the relation (7):

F = 1207 x 25^2 x 200 = 150 875 000 N = 15 087,5 x 10^3 daN.

We calculate the action of the current force on the break-water in the nature. It results:

F = 118 900 000 N = 11 890 x 10^3 daN.

If we refer only to the force of the current acting on the break-water, we notice that the difference of the total value is 26% between the “nature” and the “model” at two scales. The difference between the “nature” and the “model” at one scale is only 11%.

However, we consider that the two scales similarity method mustn’t be eliminate because it is more suggestive in the simulation of phenomena and, in a “virtual stand”, with exotic liquids, the conclusions can be different.

As I specified before, it is difficult to achieve a model for experimenting. Also it is difficult to calculate the phenomena in the nature scale using the FLUENT. So we calculated the physical parameters, using FLUENT on the model and we pass them, using the similitude criteria, in the nature.

The results obtained using the single scale similitude method are very close to the nature. The main idea is that FLUENT can be used as an experimental stand.

A mathematical model of the filling (emptying) of the lock chamber in a transition period, when the valves are opening or shutting is presented in the Chapter 7. An accuracy mathematical model of the filling (emptying) reservoir phenomena with liquid, in our case the lock chamber, presume the solving of the movement equations in the conditions very near to the reality

The potential vector is a term taken from the electro-technique, in fact a symbol used to facilitate the mathematical calculation (for the solenoidal field $\nabla \bar{v} = 0$, which involve $\bar{v} = rot \bar{A}$, $\bar{A} = \bar{A}(x, y.z.t)$ being the potential vector of the field if $\nabla \bar{A} = 0$) apparent without physical significance. The physical significance of the potential vector was put into evidence by Al. A. Vasilescu and F. Petrea: the circulation of the potential vector on the perimeter of the conduit section is equal to the flow through this conduit. The potential vector help us to solve the Navier –Stokes equations to establish the velocity distribution in the conduit.

For the transitory regimes we can consider a linear variation of the flow. In this situation, we calculated the pressure gradient on the length of the filling (emptying) conduit of the lock chamber. Having this gradient, we could establish the variation of the hydrostatic pressure and the velocity of the lock chamber water level respectively.

We shall study the flow of the viscous fluid, no compressible, in an unsteady regime, through the lock camber filling (emptying) conduits with the help of the general equation of Navier-Stokes and the equation of continuity. In our theoretical study we shall use the transcription of these equations in cylindrical coordinates (r, θ, z). Oz being the axe of the conduit.

The movement is axial-symmetric and the axe of the conduit coincides, as we already said, with the axe Oz. The components of the velocity will be:

$$\begin{aligned} v_r &= v_\theta = 0, \\ v_z &= v(r,t). \end{aligned} \tag{8}$$

As we know, the solenoidal (rotational) fields are characterized by $\nabla \overline{v} = 0$, which involve:

$$\overline{v} = rot\overline{A}, \tag{9}$$

where $\overline{A}$ is a function of point and time, which represents the potential vector of the velocities field if $\nabla \overline{A} = 0$.

The potential vector of our movement will be:

$$\overline{A} = A(r,z)\overline{\theta_0} \tag{10}$$

and it can be determinate with the relation:

$$\Delta\left(\frac{\partial \overline{A}}{\partial t} - \upsilon \Delta \overline{A}\right) = 0, \tag{11}$$

a particularization for the axial-symmetric movement of the equation of the flow of real, no compressible fluids, written using the potential vector of the velocities field.

Solving the equation (5) using the Laplace transformation and taking into account that the circulation of the potential vector on the perimeter of the conduit section is equal to the flow through this conduit we shall obtain [ ]:

$$A(r,t) = \frac{1}{2\pi i}\int_{b-i\infty}^{b+i\infty} e^{st}\frac{Q^*}{2\pi r_0}\frac{2I_1(p) - pI_0(p_0)}{2I_1(p_0) - p_0 I_0(p_0)}ds, \tag{12}$$

when I_0 and I_1 are the Bessel modify functions, rank 0, respectively 1, first sort, $p = r\sqrt{\frac{s}{\upsilon}}$ and $p_0 = r_0\sqrt{\frac{s}{\upsilon}}$.

Q^* is the Laplace transformation of the flow.

Knowing that the velocity is:

$$v = v_z = \left(rot\overline{A}\right)_z, \tag{13}$$

we shall obtain the relation of the velocity:

$$v(r,t) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} e^{st}\frac{Q^*}{\pi r_0}\sqrt{\frac{s}{\upsilon}}\frac{I_0(p)-I_0(p_0)}{2I_1(p_0)-p_0 I_0(p_0)}ds. \tag{14}$$

We consider a linear variation of the flow in the filling (emptying) conduit. In this case, we propose to evaluate the variation of the level in the lock chamber.

So, the flow has a linear variation:

$$Q(t) = k_1 t + k_2. \tag{15}$$

By applying Laplace transformation, we'll obtain:

$$Q^*(s) = \frac{k_1}{s^2} + \frac{k_2}{s} = \frac{k_1 + k_2 s}{s^2}. \tag{16}$$

The expression of the potential vector becomes:

$$A(r,t) = \frac{1}{2\pi i}\frac{1}{2\pi r_0}\int_{b-i\infty}^{b+i\infty} e^{st}\frac{k_1 + k_2 s}{s^2}\frac{2I_1(p)-pI_0(p_0)}{2I_1(p_0)-p_0 I_0(p_0)}ds. \tag{17}$$

Solving the integrative, we'll have:

$$A(r,t) = \frac{1}{2\pi r_0}\left[(k_1 t + k_2)\frac{r}{r_0}\left(2-\frac{r^2}{r_0^2}\right) - k_1\frac{r\left(r^2-r_0^2\right)^2}{24\upsilon r_0^3} - 2\frac{r_0^2}{\upsilon}\sum_{n=1}^{m} e^{\frac{\upsilon}{r_0^2}\alpha_n^2 t}\frac{k_1 - k_2\frac{\upsilon}{r_0^2}\alpha_n^2}{\alpha_n^4}\frac{2J_1\left(\frac{r}{r_0}\alpha_n\right)-\frac{r}{r_0}\alpha_n J_0(\alpha_n)}{J_1(\alpha_n)}\right]; \tag{18}$$

and

$$v(r,t) = \frac{1}{\pi r_0}\left[(k_1 t + k_2)\frac{1}{r_0}\left(1-\frac{r^2}{r_0^2}\right) - k_1\frac{r\left(r^2-r_0^2\right)^2\left(3r^2-r_0^2\right)}{48\upsilon r_0^3} - \frac{r_0^2}{\upsilon}\sum_{n=1}^{m} e^{-\frac{\upsilon}{r_0^2}\alpha_n^2 t}\frac{k_1 + k_2\frac{\upsilon}{r_0^2}\alpha_n^2}{\alpha_n^3}\frac{J_0\left(\frac{r}{r_0}\alpha_n\right)-\frac{r}{r_0}\alpha_n J_0(\alpha_n)}{J_1(\alpha_n)}\right]. \tag{19}$$

To determine the pressure gradient, we shall use the Navier-Stokes equation, written in cylindrical coordinates, neglecting the masse forces (the third equation (1)) in which $v_r = v_\theta = 0, v_z = v(r,t)$:

$$-\frac{\partial p}{\partial z}=\rho\frac{\partial v}{\partial t}-\eta\left(\frac{\partial^2 v}{\partial t^2}+\frac{1}{r}\frac{\partial v}{\partial r}\right). \quad (20)$$

We will finally obtain the pressure gradient in the case of known linear variation of the flow:

$$-\frac{\partial p}{\partial z}=\frac{4\rho}{\pi r_0^2}\left[\frac{1}{3}k_1+\frac{2\upsilon}{r_0^2}(k_1 t+k_2)-\sum_{n=1}^{m}e^{-\frac{\upsilon}{r_0^2}\alpha_n^2 t}\frac{k_1-k_2\frac{\upsilon}{r_0^2}\alpha_n^2}{\alpha_n^2}\right]. \quad (21)$$

We have established the pressure gradient formula in the case of linear variation of the flow. Now we are interested in the variation of the lock chamber liquid level. We want to know the velocity of this level when the pumps fill the lock chamber. For this, denoting with f(t) the left part of the relation (26) we can write:

$$dp=-f(t)dz\,. \quad (22)$$

By integration the relation (27) on the length of the filling conduit, we shall obtain:

$$p_2-p_1=-f(t)(z_2-z_1) \quad (23)$$

or

$$p_1-p_2=f(t)l\,, \quad (24)$$

l being the length of the conduit.

If p_1 is the constant hydrostatic pressure from the pool I and h_2 the level of the lock chamber liquid we'll have successively:

$$p_1-\rho g h_2=f(t)l\,;$$

$$\rho g h_2=p_1-f(t)l\,;$$

$$u(t)=\frac{h_2}{t}=\frac{1}{\rho g t}[p_1-f(t)l]; \quad (25)$$

u(t) represents the rising velocity of the level.

By replacing f(t), we'll have:

$$u(t)=\frac{p_1}{\rho g t}-\frac{4l}{\pi g r_0^2}\left[\frac{1}{t}\left(\frac{k_1}{3}+\frac{2\upsilon k_2}{r_0^2}\right)+\frac{2\upsilon k_1}{r_0^2}-\sum_{n=1}^{m}\frac{1}{t}e^{-\frac{\upsilon}{r_0^2}\alpha_n^2}\frac{k_1-k_2\frac{\upsilon}{r_0^2}\alpha_n^2}{\alpha_n^2}\right]. \quad (26)$$

The mathematical model allows us to solve a quite delicate problem: the variation of the liquid level in the lock chamber in a transition period - the opening of a valve for example. The valve opening can be made thus the flow be linear. Solving Navier-Stokes equations using the potential vector, we have been able to establish the velocity variation in the conduit and the liquid level variation in the lock chamber.

The problem can be formulated conversely: taking a certain velocity, constant, of the liquid level, we'll determine the necessary flow for this level variation. In this situation the pressure gradient has a linear variation $\frac{\partial p}{\partial z} = at$, where a is a dimensional constant.

Finally we present the main personal contributions of the thesis:

1. A synthesis of forces acting on the hydro-structure (break-waters, channels, barrages, locks, etc.).
2. Action wind simulation of the superior part of the break-waters.
3. Flow model through a broken barrage.
4. Using FLUENT programme as an experimental stand.
5. Two scales similarity for the long break-waters.
6. The pressure gradient at a linear variation of the flow with application in the calculation of the lock liquid level variation – mathematical model.
7. Determination of the flow in the case of constant velocity of the liquid level.