Flexible concrete protective coating resistance to approach flow exposure

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Abstract. In order to protect the bottom and coastal slopes of natural channels and artificial reservoirs from channel deformations, various shore reinforcing structures are often used. One of the structures is the universal flexible protective concrete coating. When using this kind of structures, it is necessary to take into account their interaction with the approach flow. At the flexible protective coatings operating, one of the problems is the “wrapping” of the coating body. To calculate the stability assessment of the surface coating, it is necessary to know the value of the coefficient of hydrodynamic resistance of the protective coatings. It is determined mainly by its shape. Currently, various forms of surface coatings from various materials are used. In most cases, the resistance of such structures is assumed approximately, based on the known values of the resistance coefficients of bodies of various shapes. As a rule, the elements of protective coatings have a specific form, the resistance of which must be established experimentally. The article presents the results of an experimental determination of the hydrodynamic drag coefficient of a universal flexible concrete protective coating (a universal flexible protective mat) on aerodynamic and hydraulic experimental stands. Used laboratory equipment with basic operating characteristics, examples of experimental models, and basic operating conditions during experiments are described. It is shown that the value of the coefficient of hydrodynamic resistance decreases with increasing Reynolds number. The obtained values of the hydrodynamic resistance coefficient in some cases exceed the values recommended for calculating the maximum permissible flow velocity when assessing the stability of a protective coating. It is concluded that it is necessary to experimentally evaluate the hydrodynamic resistance coefficient for each model of protective coatings. The recommended value of the hydrodynamic resistance coefficient for the studied modification of a flexible protective concrete coating is established.

1. Introduction

To strengthen the coastal slopes of the canals, to prevent deformation of the channels, one of the reasons for which is the influence of channel and filtration water, as well as in the process of reconstruction of engineering structures at water bodies, universal flexible concrete protective coatings are used.

Shores and slopes can be made up of unstable soils that are less resistant to erosion, and, as a result, slopes can be showered at flow velocities greater than the values allowed for erosion [8]. One of the problems is that only a small part of the soil is carried downstream [4,5], the main volume of soil settles to the bottom of the channel, and the bottom marks and water level markings increase. The
situation can develop in the opposite way, based on the geomorphological features of the territory. For example, the slopes of the channels are composed of stronger soil than the bottom, in which case the bottom will be most susceptible to erosion [8]. The main cause of erosion in this case is the accept stream of a higher order, which creates a backwater in this part of the channel and contributes to sediment deposition. To avoid the above negative factors of canal erosion during construction, the bottom and shores of water bodies are strengthened with various protective structures, including flexible concrete mats.

Despite the fact that the designs of flexible protective concrete coatings have been developed and applied for a long time [15,20], to date there are no reliable calculations on the use of universal mats, confirmed by experimental data.

Let consider the use of flexible protective concrete coatings [9] in order to strengthen the bottom of the channel. The main operational problems in this case are the loss of stability and the displacement (twisting and drift) of the protective coating.

2. Methods
To prevent the displacement of the protective coating, it is necessary to conduct an analysis of its operation under conditions of interaction with the approach flow. It is necessary to evaluate the force interaction of the coating and the flow. For this purpose, the calculation technique of the force action of the flow on the protective coating is specified on the basis of the obtained experimental data on the determination of the hydrodynamic resistance coefficient. Previous calculation and theoretical studies of the hydrodynamic effect of the flow [6] on protective structures showed that the process of the protective coatings twisting begins with separation from the bottom of the base of the first row of blocks, which was confirmed by experimental studies using the PIV method (Figure 1) carried out in the educational research and production laboratory for aerodynamic and aerospace testing of building structures of the National Research Moscow State University of Civil Engineering [11].

Figure 1 shows the velocity distribution in a stream approaching onto a flexible concrete protective coating. If can be seen that the air flow approaching onto the protective coating creates a separation zone before the first row [16, 17] - velocity vectors in front of the base the protective coating is directed vertically upward, which creates the conditions for the separation of the first row of protective structures from solid boundaries.

![Figure 1. Velocity distribution on the way to universal flexible protective concrete mats](image-url)
It should be noted that the first row of protective coating is in the most difficult conditions of interaction with the flow, therefore, in order to calculate the twisting of the protective coating, it is necessary to take into account the interaction of the first row of protective coatings.

In existing calculation methods [19], the drag $F_c$ is determined based on the hydrodynamic effect of the water flow on concrete blocks

$$F_c = C_D S \frac{\rho U^2}{2}, \quad (1)$$

where $C_D$ is the coefficient of hydrodynamic resistance of the protective coating; $S$ is the mid-sectional area; $U$ is the velocity of approach.

According to A.D. Altshul, the hydrodynamic resistance coefficient of the considered flexible concrete protective coating up to the present is recommended to be taken equal to 1.5 for a cylindrical body having a rectangle in cross section, with faces directed at an angle of 45° to the flow [1,7]. For the most accurate determination of the force of the hydrodynamic effect of the flow on the protective coating, experimental studies were conducted to determine the coefficient of hydrodynamic resistance [18].

Experimental studies were carried out in two scientific laboratories at the National Research Moscow State University of Civil Engineering. In the first case, the flexible protective concrete coating (universal flexible protective concrete mats) [10] was located on a flat horizontal bottom in the working chamber of the US Aerolab Educational Wind Tunnel subsonic wind tunnel (Figure 2), the size of the working chamber of the pipe is 30.5×30.5×61 cm.

![Figure 2. Aerolab Educational Wind Tunnel wind tunnel](image)

The second part of the experimental studies was carried out in a hydraulic experimental channel (Figure 3) in the laboratory of Hydraulics and Hydromechanics of the National Research Moscow State University of Civil Engineering [14]. The main characteristics of the channel: the length of the working section of the channel – 12.5 m; channel width – 311 mm, maximum water depth in the channel – 450 mm. Model of universal flexible protective concrete mats for hydraulic channel is presented in the Figure 4.

![Figure 3. Hydraulic experimental channel](image)

![Figure 4. Model of universal flexible protective concrete mats for hydraulic channel](image)
One of the objectives of the experiment was to determine the resistance coefficient of the protective coating.

3. Results and discussions.
Simulation in a wind tunnel was carried out at a scale of 1:8, models [10] were installed in the working chamber of the pipe on a six-axis force and moment sensor FTS-Mini-45 SI-290-10. Data from the device were transferred and recorded on a computer [2].

Experimental values of the resistance coefficient of the flexible protective concrete coating were determined by the formula

$$C_D = \frac{2F_c}{\rho U^2 S}.\quad (2)$$

For the calculation, the obtained experimental values of the force components were taken; an example of the obtained values is given in Table 1.

According to the formula (2), the hydrodynamic resistance coefficient for the universal flexible protective concrete mats was determined (Table 2).

| Mmeasurement number | $F_x$ | Mmeasurement number | $F_x$ |
|---------------------|-------|---------------------|-------|
| 1                   | 0.3563| 11                  | 0.35  |
| 2                   | 0.3615| 12                  | 0.3469|
| 3                   | 0.3564| 13                  | 0.3463|
| 4                   | 0.3474| 14                  | 0.348 |
| 5                   | 0.3489| 15                  | 0.3556|
| 6                   | 0.3489| 16                  | 0.3539|
| 7                   | 0.3524| 17                  | 0.3584|
| 8                   | 0.36   | 18                  | 0.3603|
| 9                   | 0.3608| 19                  | 0.357 |

| Mmeasurement number | $C_x$ | Mmeasurement number | $C_x$ |
|---------------------|-------|---------------------|-------|
| 1                   | 1.47833| 11                  | 1.45246|
| 2                   | 1.5001 | 12                  | 1.43959|
| 3                   | 1.47891| 13                  | 1.43706|
| 4                   | 1.44133| 14                  | 1.44402|
| 5                   | 1.44778| 15                  | 1.47571|
| 6                   | 1.44772| 16                  | 1.46865|
| 7                   | 1.46219| 17                  | 1.48707|
| 8                   | 1.49365| 18                  | 1.49516|
| 9                   | 1.49693| 19                  | 1.4812 |

The value of the hydrodynamic resistance coefficient obtained on the aerodynamic bench at $U = 8.6$ m/s is close to the values proposed in the calculation method [3]: $C_D = 1.466$. Also, the value of the hydrodynamic resistance coefficient was determined by the results of experiments in the hydraulic channel. To assess the stability of the first row units to capsize, it is necessary to know the lifting force, weight and longitudinal component of the resistance force. The
The longitudinal component of the resistance force was determined by the energy loss by the flow on the first row of blocks of the protective mat (Figure 5).

Energy losses by flow were determined using the Bernoulli equation, composed for two sections: section 1-1 - directly in front of the block, section 2-2 - behind the block:

\[ z_1 + h_1 + \frac{\alpha U_1^2}{2g} = z_2 + h_2 + \frac{\alpha U_2^2}{2g} + h_w , \]  \hspace{1cm} (3)

where \( z_1, z_2 \) are marks of the lower points of the calculated sections (due to the small longitudinal block size with a design slope of 0.001, the values differ slightly and are assumed to be the same);
\( \alpha \) is the Coriolis coefficient, assumed constant and equal to 1.05 [12];
\( u_1, u_2 \) are average velocities in sections 1-1 and 2-2, determined by the surface flow rate and the corresponding depths \( h_1, h_2 \) with the same channel width \( b = 0.31 \text{ m} \).

Determining the total loss of energy, taking into account the weight flow rate and the flow passage time over the mat, we find the work performed by the flow against the resistance force acting on the flow by one block:

\[ A = \frac{\rho g Q h_w T}{4} , \]  \hspace{1cm} (4)

where \( Q \) is the consumption of the flow part above the mat;
\( T \) is the flow time over the block, \( T = \frac{L_2}{U_{av1-2}} \); where \( L_2 \) is the hydrodynamic interaction surface from section 1-1 to section 2-2, for the universal flexible protective concrete mats \( L_2 = 0.085 \text{ m} \);
\( U_{av1-2} \) is the average flow rate above the block when it moves from section 1-1 to section 2-2.

The determined energy losses by the flow within one block can be considered as the work of the resultant longitudinal resistance force along the length of the block, which allows us to determine the longitudinal resistance force:

\[ A = F_c l_1 . \]  \hspace{1cm} (5)
Then, writing down the general expression for the resistance force of a streamlined body [13]:

$$F_c = C_D S_m \rho \frac{U^2}{2},$$  \hspace{1cm} (6)

we determine the hydrodynamic resistance coefficient of the block $C_D$ by the formula (2).

When calculating the force $F_c$ and the coefficient $C_D$, the magnitude of the hydrodynamic interaction surface was conventionally assumed to be the same. For a more accurate calculation, a more detailed study of the flow pattern of the block is required. The calculation results are given in Table 3.

### Table 3. Calculation results

| $Q$, m$^3$/h | $h_1$, m | $h_2$, m | $Q_p/Q_0$ | $U_1$, m/s | $U_2$, m/s | $h_1$, m | $T$, s | $A$, Nm | $F_c$, N | $C_D$ | Re-10$^3$ |
|-------------|---------|---------|-----------|-----------|-----------|---------|-------|--------|--------|-------|----------|
| 20          | 0.0576  | 0.0507  | 0.84      | 0.261     | 0.297     | 0.0058  | 0.305 | 0.020  | 0.271  | 1.86  | 70       |
| 60          | 0.1055  | 0.0974  | 0.91      | 0.464     | 0.502     | 0.0061  | 0.176 | 0.040  | 0.534  | 1.22  | 225      |
| 110         | 0.1484  | 0.1393  | 0.94      | 0.624     | 0.665     | 0.0062  | 0.132 | 0.058  | 0.773  | 0.99  | 445      |

The calculation results using experimental data (Table 3) showed that the hydrodynamic resistance coefficient of flexible protective concrete blocks is not constant and decreases with an increase in the Reynolds number for the flow approaching onto the block.

### 4. Conclusions

For the most accurate calculation of protective coatings resistance to approach floe exposure, it is necessary to experimentally determine the value of the hydrodynamic resistance coefficient for each coating model.

As a result of the studies, the experimental value of the hydrodynamic resistance coefficient of a flexible concrete protective coating (universal flexible protective concrete mats) was established. The hydrodynamic resistance coefficient obtained at Reynolds numbers less than 500·10$^3$ depends on the Reynolds number. Thus, when calculating the limiting flow velocity, which includes the coefficient of hydrodynamic resistance:

$$U_k \geq \sqrt{\frac{2}{C_D S \rho}} \left[ f(G + P - P_a) + F_g \right],$$ \hspace{1cm} (7)

the highest value of the hydrodynamic resistance coefficient should be 1.9, which ensures the necessary margin of stability of the protective coating. (Here $G$ – force of gravity; $P$ – hydrostatic loading force; $P_a$ – Archimedes power; $F_g$ – ground bonding strength.)

The most accurate knowledge of the value of the hydrodynamic resistance coefficient will more accurately determine the limiting velocity at which the first row of protective coatings can twist. Nowadays it is one of the most common operational problems.

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