The Calculating Dynamics Erosion of Support Foundations of Ocean-Technical Installations

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Abstract. The article discusses an approach to calculating the characteristics of soil erosion near the support foundations of ocean-technical structures under the influence of wave and constant currents. Vertical supports in the form of a circular cylinder are considered a support base. An example of the choice of the initial and boundary conditions for the calculation is given. Simulation is carried out near the cylindrical support. The results obtained were compared with empirical data. Conclusions are drawn about the displacement of the zones of maximum and minimum velocities during wave movement. The spatial distribution of the amplitudes of the wave velocities was calculated. A decrease in the amplitude in the rear part of the cylinder and immediately in front of its frontal part was revealed, and it was also determined that the zone of an increase in the amplitude was formed near the lateral surfaces of the cylinder.

1. Introduction
Currently, there are several methods for modeling the erosion of the support foundations of ocean engineering systems. Basically, for their application, it is necessary to calculate the three-dimensional velocity field of the flow around structural elements by wave and constant currents, and then use the obtained velocity fields to calculate turbulent stresses near the bottom surface and the conditions for the transfer of the bottom material in a suspended state or directly on the bottom surface. There are a large number of works devoted to experimental, theoretical, and numerical methods for studying the structure of a viscous fluid flow around various obstacles [1-7]. Nevertheless, this problem cannot be considered solved, since in a turbulent flow regime (Re >> 10³), the solution of the basic hydrodynamic equations becomes unstable even with a relatively fine computational grid and a small-time step. To solve nonstationary problems associated with the interaction of various flows with streamlined objects, the averaging of the Navier-Stokes equations according to Reynolds is used [8], and at the same time, there is a well-known problem of parametrization of the subgrid stress tensor [9, 10]. In the simplest case, a hypothesis of Boussinesq is used [11,12,13]. Following the hypothesis, the tensor is expressed in terms of the gradients of the averaged components of the flow velocity and a constant value - the coefficient of turbulent viscosity νₜ. This makes it possible to formally replace the coefficient of kinematic viscosity with some constant value νₜ, which is ambiguous and, as a rule, is selected from the condition of obtaining a stable solution under given boundary conditions, computational grid, and time step. This method is still relatively widely used in solving various hydrodynamic problems and in geophysical hydrodynamics [14, 15]. At the same time, relatively complex software which provides for the use of various LES methods for spatial hydrodynamic calculations is being created. These include, for
example, software Fluent [16], COSMOSFloWorks. COSMOSFloWorks also uses Reynolds' averaging of Navier-Stokes equations, where turbulent effects are considered as flow parameters or large-scale time-dependent effects. To close the system of equations, transport equations are used for the kinetic energy of turbulence and the rate of its dissipation per unit volume (the so-called $k-e$ model) [17]. In this case, the same system of equations is used to describe laminar and turbulent flows. This article considers an approach to the three-dimensional hydrodynamic calculation of the velocity field when a constant current flows around vertical support (in the form of a circular cylinder) of an ocean-technical installation, and also determines the characteristics of soil erosion near the support. The results of such numerical modeling are compared with the data of known experimental studies of such flows. The considered approach is adapted for the application of COSMOSFloWorks. The solution to these problems determines the possibility and prospects of using COSMOSFloWorks as a modern tool for studying the impact of natural currents on structural elements of such ocean-technical systems as offshore drilling platforms, subsea pipelines, terminals, and others.

2. Result
Let us consider the numerical calculation of the structure of the velocity field and the characteristics of soil erosion near the vertical support of the ocean-technical installation under the influence of constant and wave currents with the help of COSMOSFloWorks.

Vertical cylindrical supports are widely used in installations for offshore development, as well as for studying the dynamics of the bottom topography under the action of waves and currents in controlled laboratory conditions. The design diagram of the flow around the cylinder is shown in Figure 1.

![Figure 1. The design scheme of flow around a vertical cylinder.](image)

To solve a three-dimensional non-stationary problem, the dimensions of the computational domain are set along the axes $ox, oy, oz$, which are 10 ... 15 times larger than the dimensions of the streamlined cylinder.

The boundary conditions are defined as follows:

1. The geometry of the streamlined cylinder – the coordinates of its surface in the base coordinate system are determined. The adhesion condition is set on a solid surface of the streamlined object.

2. On the boundary planes $AA'C', ABCD$ and $A'D'C'B'$, a constant flow velocity $u_1 = U_0$ (along the $ox$ axis) is set.

3. At the boundary of the outflowing stream (plane $BB'DD'$), the Sommerfeld condition [18] is set for the normal components of the velocity.

As the initial conditions, a uniform flow with a constant velocity $U_0$ directed along the $ox$ axis is
specified. Taking into account the turbulent nature of the flow, the turbulence intensity \( I_t \) and the mixing path \( I_p \) are specified [19]. The basic computational mesh is set in the form of evenly distributed rectangular cells, the number of which is determined by the size of the computational domain and the streamlined object. Numerical calculations of the velocity field were performed when flowing around a cylinder of large aspect ratio \( (l/D \gg 1) \) and a cylinder of short aspect ratio \( (l/D = 1) \) at Reynolds numbers \( (Re) \) in the range \( 10^3 \ldots 10^7 \).

Simulation of soil erosion near-vertical cylindrical support \( (D = 1\text{m}) \) was carried out at a flow velocity of 0.65 m/s. The design depth is 10 m, \( \nu=1.2 \cdot 10^{-6} \text{m}^2/\text{s} \), the type of soil is fine shell sand. The dimensions of the computational domain are \(-5 \ldots +20 \text{ m} \) along the \( \alpha x \) axis, \(-5 \ldots +5 \text{ m} \) along the \( \alpha y \) -axis, and \(-10 \ldots 0 \text{ m} \) along the \( \alpha z \) -axis. The results of calculating the velocity field are shown in Figure 2.

![Figure 2](image)

**Figure 2.** The flow around a cylinder of finite length at \( Re = 10^6 \).

The calculation results showed that within an hour the depth changes do not exceed one centimeter. In 12 hours, the amount of washout reaches 5.5 cm, and the washout \(-1.5 \text{ cm} \). Over the first day, the washout increases to 7 cm, for the second \(-10 \text{ cm} \), and for the third \(-16 \text{ cm} \). Maximum washout for the same intervals time is 4, 6, and 10 cm, respectively. Areas of soil washout are located in the frontal and rear parts of the cylinder, areas of washout are located near the side surfaces. An interesting feature of the bottom structure is the formation of zones of erosion and soil reclamation in the wake of the flow around the cylinder at a distance of \( 5 \ldots 8 \text{ m} \) from its center.

3. **Discussion**

Comparison of simulation results with empirical data based on the SRICOS-EFA method [20]. Following this method, the time dependence of the erosion depth is calculated by the formula

\[
z(t) = \frac{t}{(t/z_{\text{max}}) + (1/z^*}, \quad \text{where; } z_{\text{max}} = 0.00018k_f Re^{0.635}, \quad k_f \text{ – the coefficient of the shape of the streamlined object, for a cylinder its value is equal to } 1; \quad Re = \frac{UD}{\nu} \text{ – Reynolds number; } z^* \text{ – is the initial erosion rate, which corresponds to the turbulent stress near the bottom } \tau_{\text{mix}} = 0.094\rho U^2k_f(1/\log Re -0.1).\]

The comparison results showed that the difference between the calculations does not exceed 5%.
Numerical calculations of the wave flow around a vertical cylinder were performed with the following initial data: sea depth $H = 10$ m, wind speed $W = 20$ m/s, water temperature $t = 15^\circ C$, soil type - fine shell sand. The average particle size of the bottom material is 0.466 mm.

Average wave height $h_w = 2a$, period $T_w$, length $\lambda$, the amplitude of wave velocity $U_{m0}$, and horizontal displacements $a_w$ are equal, respectively: 1.23 m, 4.7 s, 46.2 m, 0.46 m/s, and 0.34 m; the amplitude of the wave velocity is 0.615 m.

Kinematic viscosity of water $\nu = 1.24 \times 10^{-6}$ m$^2$/s, maximum Reynold wavenumber $Re = 496$, the thickness of wave bottom boundary layer $L_B = 0.18$ m. Constant current velocity $U_p = 0.2$ m/s, the thickness of bottom boundary layer $\Delta = 3.3$ m, mixing path $l = 0.0097$ m, turbulence intensity $I_t = 0.011$.

As mentioned above, the flow around the cylinder is shown in Figure 1. The wave propagates along the axis $ox$.

The boundary conditions for calculating the wave velocity are determined as follows.

1. On the plane AA’CC’ the wave velocity field is set in the following form:
$$u(x, z, t, y) = \frac{\omega a \sinh(kz)}{\sinh(kH)} \sin(\omega t - kx), \quad -H \leq z \leq 0, \quad -L_{ox} \leq x \leq L_{ox}, \quad v(x, z, t, y) = 0.$$  

The wave propagates along the axis $ox$.

The pressure field is set on the free surface (plane ABCD)
$$p(x, y, t) = p_g \frac{\sinh(kz)}{\sinh(kH)} \sin(\omega t - kx), \quad z = 0, \quad -L_{ox} \leq x \leq L_{ox},$$

where $\omega = 2\pi / T_w$ – circular frequency of wave vibrations; $k = 2\pi / \lambda$ – wave number; $a$ – wave amplitude.

2. On the plane DBB’D’, the Sommerfeld radiation condition is set for the normal components of the flow velocity, i.e. $\frac{\partial u}{\partial t} = 0$.

3. On the surface of the cylinder and the bottom ($z = 0$), the condition of equality to zero of the flow velocity is satisfied, i.e. $u = v = w = 0$.

The boundary conditions for calculating mean flow disturbances are determined as follows.

1. On the sea surface (plane ABCD) and the plane, the drift velocity of the current $U = 0.2$ m/s is set. The bottom boundary layer is not taken into account in this problem, since the solution uses the vertical average flow velocity $U(x, y)$.

2. On the plane DBB’D’, the Sommerfeld radiation condition is set in the following form $\frac{\partial u}{\partial t} = U \frac{\partial u}{\partial x}$.

3. On the surface of the cylinder and the bottom ($z = 0$), the condition of equality to zero of the flow velocity is satisfied, i.e. $u = v = 0$.

Since the phase velocity of the wave is approximately 10 m/s, and the velocity of the constant flow is 0.2 m/s, there is practically no interaction between the constant and the wave velocity and these fields can be considered independently, i.e. solve two problems – one for wave velocity, the other for constant flow.

Figure 3 shows the results of the distribution of the wave velocity of the flow around the cylinder with the indicated interval. Figure 4 shows the results of calculations of erosion and washout of bottom material near the vertical cylinder, calculated for the above conditions and for different time intervals.
Figure 3. The unsteady wave field of flow velocity around a vertical cylinder.

Figure 4. Spatial distribution of erosion and alluvial bottom material for different time intervals. Local depth scale in meters.

The shift of the zones of maximum and minimum velocities during wave movement is noticeable. Having the data on the wave velocity field at each point of the calculation scheme, the spatial distribution of the wave velocity amplitudes was calculated. Its feature is a decrease in amplitude in the rear of the cylinder and immediately in front of its frontal part. Zones of increasing amplitude are formed near the lateral surfaces of the cylinder.

Based on the results of calculations, conclusions can be drawn. Within an hour, changes in depth do not exceed one centimeter. In 12 hours, the amount of washout reaches 5.5 cm, and the washout - 1.5 cm. Over the first day, the washout increases to 7 cm, for the second - up to 10 cm, and for the third - up to 16 cm. Maximum washout for the same time intervals is 4, 6, and 10 cm respectively. Areas of
soil erosion are located in the frontal and rear parts of the cylinder, areas of alluvial soil are located near the side surfaces. An interesting feature of the bottom structure is the formation of zones of erosion and alluvial soil in the wake of the flow around the cylinder at a distance of 5 ... 8 m from its center.

4. Conclusion
COSMOSFloWorks, used to calculate unsteady three-dimensional fields of flow and pressure when flowing around a cylinder of large elongation, provides reproduction of the main features of the formation of a vortex wake behind the cylinder. These features are known from the results of experimental studies. These include a change in the angle of flow separation from the cylinder surface during the development of a wake, a structure of the velocity field close to potential flow at the initial stages of wake formation, the formation of two symmetric vortices in the wake at the development of instability of the interface between these vortices and, as a consequence, their violation. symmetry. At the same time, the simulation does not fully reproduce the structure of secondary vortices, which, according to experimental data, are formed in the zones between the main flow and large wake vortices, and regions of small-scale turbulence, which are generated in the wake at high Reynolds numbers, are not reproduced either.

The estimation of the turbulence parameters when setting the initial conditions, which has been substantiated, ensures the functioning of the COSMOSFloWorks for calculating unsteady three-dimensional velocity and pressure fields when flowing around cylindrical objects. Thus, the COSMOSFloWorks can be used to create three-dimensional eddy-resolving models of unsteady velocity and pressure fields when studying the interaction of sea currents with ocean-technical systems of complex configuration. In this case, the structure of the velocity and pressure fields is reproduced, including large-scale eddies with sizes that correspond to the scales of the computational grid. This feature corresponds to the initial formulation of the problem of obtaining the flow velocity and pressure fields by the LES method. The model reproduces quite well such integral characteristics of the flow as the dependence of the drag coefficients and Strouhal numbers on the Reynolds numbers.

5. References
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