The algorithmic approach for calculating dynamics erosion of support foundations of ocean-technical installations

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Abstract. The article discusses the structure, the main algorithms for ensuring the functioning of the program for calculating the characteristics of soil erosion near the support foundations of ocean-technical installations under the influence of waves and constant currents. The description of the blocks of the interface module and the calculation module is given. The main calculation formulas are given. Based on the introduced computational scheme of the flow around a vertical cylinder and the formulated scheme for setting the boundary conditions, an example of the program operation when calculating soil erosion is given. Areas of soil erosion and areas of soil reclamation are shown.

1. Introduction
When designing ocean-technical systems for the development of the shelf, it is not always possible to prepare the seabed surface, which could ensure stable operation of the installation over long periods. The seabed surface is usually represented by low-bearing soil (sand, liquid silt), and at the same time, significant velocities of constant and wave bottom currents are possible in the shelf zones. When these currents interact with the support foundations of ocean-technical installations and the bottom surface, complex fields of current velocity and pressure are formed in the form of vortex-wave structures and small-scale turbulence. Under certain conditions, these fields can affect the bottom material in such a way that it begins to move along the bottom surface and rise upward, forming suspended sediment profiles. These processes lead to a change in the structure of the bottom and the immediate vicinity of the support foundations of ocean-technical installations. Under them, deep gullies can form, which reduces the stability of the installation at the bottom. In some critical cases, they can lead to an unacceptable tilt or overturn. The intensity of soil erosion processes increases under storm conditions when external loads on the installation from wind, waves, and currents also increase. During the passage of Hurricane Katrina in the Gulf of Mexico, a large number of drilling platforms were damaged. Some of them capsized and damaged underwater pipelines. Another feature of the processes of erosion of the support foundations of ocean-technical installations is the integral effect of the gradual development of erosion of bottom material under moderate hydrometeorological conditions. This process at a certain point in time can lead to the loss of stability of the installation on the ground. Thus, the erosion of the support foundations of ocean-technical (in the general case, hydro-technical) installations under the influence of waves and currents is one of the most urgent problems of their design and operation. A large number of studies have been devoted to this issue [1-4].

At present, the following trend has been adopted and is developing in modeling the erosion of the support foundations of ocean-technical installations. Its key points are [5]:

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1. creation of a geometric model of a streamlined object, for example, in AutoCAD; 2. import of this model into the computational domain for numerical calculations of the flow velocity and pressure fields; 3. calculations of the fields of wave and constant currents that are formed when flowing around an object using CosmosFloWorks; 4. calculations of the specific transport of bottom material directly above the bottom surface and in the form of suspended material; 5. calculation of changes in the depth of the seabed during the formation of zones of erosion and alluvial soil; 6. re-calculation of the hydrodynamics of the flow around the installation taking into account changes in the boundary conditions on the bottom surface due to changes in its depth; 7. calculations of the values of transfer of bottom material directly above the bottom surface and in the form of suspended material; 8. re-calculation of changes in the depth of the seabed during the formation of zones of erosion and alluvial soil under new boundary conditions at the bottom. This calculation is repeated either for a given time interval or until an equilibrium state is established, at which the depth change becomes insignificant.

Now there are studies that, with this direction of modeling, provide sufficiently convincing evidence of the correspondence of the calculation results to the data of laboratory experiments [1-4]. Adhering to this trend in general, the goal of this work is to develop algorithms and software for calculating the dynamics of sea soil to improve the design and operation management of support foundations that ensure their stability against erosion.

2. The mathematical method for calculating dynamics erosion of support foundations of ocean-technical installations

Let us consider the mathematical relationships used in calculating the erosion of the base of an ocean-technical installation. The calculation of the erosion of the base of the ocean-technical installation is directly related to the main characteristics of waves and constant current. Suppose that the direction of wave propagation and the direction of the constant current coincide with the direction of the wind. We also assume that we are considering flat bottom conditions. In this case, as a model of surface waves, we will consider the LOGOIN model [6].

We will consider the following parameters as external conditions: 1. Sea depth $H$; 2. Average water temperature $t$. The kinematic viscosity of water, depending on its temperature, is calculated by the ratio $\nu = [1.38-0.028t-10]\times10^6$; 3. Wind speed $W$, its direction $\phi_w$, degree, and duration; 4. Characteristics of the soil.

Based on these data the main characteristics of waves and constant flow can be calculated.

Average wave height $h_w$, period $T_w$, and length $\lambda$

$$h_w = 0.07W \left( \frac{W}{g} \right)^{0.6}, \quad T_w = 18.7 \left( \frac{W}{g} \right) \left( \frac{gh_w}{W^2} \right)^{0.6}, \quad \lambda = T_w \sqrt{gh}, \quad g = 9.81, \tag{1}$$

Amplitudes of the bottom orbital velocity $U_{mo}$ and longitudinal oscillations of water particles in the wave motion $a_w$

$$U_{mo} = \frac{\nu h_w}{T_w \sin \left( \frac{2\pi h}{\lambda} \right)}, \quad a_w = \frac{U_{mo} T_w}{2\pi}. \tag{2}$$

Further, according to the known [6] relationships, the current velocity $U$ in the coastal zones is calculated.

The indicated parameters of waves, the direction of their propagation, the speed of a constant current, and its direction can be set regardless of the wind speed.

If the soil is heterogeneous and consists of several layers of non-cohesive (sandy) soil and an underlying layer or layers of cohesive soil (for example, loam), it is necessary to determine the equivalent diameter of the cohesive soil for each layer.
\[
d_s = d \left[ \frac{6C}{gd} + \frac{(\rho_s - \rho)tg\varphi_s}{(\rho_c - \rho)tg\varphi_c} \right]^{-0.333}
\]

where \( C \) is the adhesion force, \( S = \pi d^2 \) – area of a spherical particle; \( d \) is its average diameter, \( P = g(\rho_s - \rho)\pi d^3/6 \) is the weight of a spherical sand particle in water, \( P_c = g(\rho_c - \rho)\pi d^3/6 \) – the weight of an equivalent particle of cohesive soil in water, \( \rho_s, \rho_c \) – specific gravity of sand and cohesive soil, \( \rho \) is the specific gravity of water, \( tg\varphi_s, tg\varphi_c \) – parameters (coefficients of friction) corresponding to sand and cohesive soil.

To describe the geometric model of the investigated ocean-technical installation, the following data are entered:

- linear dimensions in plan (for example, length and width for the base of the marine platform, diameter - for a cylindrical structure);
- the coordinates of the intersection of the symmetry axes of the structure in the coordinate system of the design scheme.

Snapping to the computational grid is performed automatically. As a computational grid, a grid is taken, on which data on the flow velocity field and the deformation of the bottom surface are calculated. When determining the step of the computational grid horizontally \( \Delta g \) and vertically \( \Delta h \), it is necessary to take into account the sizes of the boundary layers at the bottom surface \( (B_L) \) and on the installation surface \( (\delta) \). To calculate the value \( \delta \), the Reynolds number \( \nu / Re = U L_u / \nu \) is determined, \( L_u \) – the size of the installation in the direction of normal flow around it with a constant flow. The thickness of the boundary layer on the lateral streamlined surface is calculated by the formula \( \delta = 0.344L_u(\log Re)^{-1.62} \) and must correspond to the horizontal step of the grid.

The initial conditions [3] are the turbulence intensity \( I_t \) and the mixing path \( l \). The definition of these parameters is carried out according to the following formulas: \( l = 0.141U L(\log Re)^{-1.62} \), \( I_t = 4.02(\log Re)^{-3.56} \).

To set the boundary conditions, the following data is required:

- Constant flow (speed \( U \) and direction \( \varphi_U \) is the angle between the velocity vector and the longitudinal axis \( oy \) of the installation, which is counted counterclockwise from the axis in the right Cartesian coordinate system \( ox \)). When specifying a constant flow in some cases, it is necessary to take into account the bottom boundary layer, the thickness of which is equal \( \Delta = \left[ 0.045U f(U) \right]^{0.25} \), \( f \) – Coriolis parameter; \( \nu \) – molecular viscosity.

- Wave flow (wave velocity profile taking into account the given direction of wave propagation \( \varphi_W \) relative to the axis \( ox \), pressure field on the free surface).

The fields of constant and wave velocity of the flow are set on the boundary surfaces of the computational grid following the given angles \( \varphi_U \) and \( \varphi_W \). On the opposite boundary surfaces, the Sommerfeld radiation condition is set for the normal components of the flow velocity. In this case, vortex disturbances are not reflected from the boundary planes of the computational grid.

Next, to calculate the dynamics of the bottom relief, the method of Ivanov and Mikhinov is used [7]. To exclude uninformative outliers in the calculation results, we use the spatial nonlinear filtering of the fields \( q_z(x, y) \) and \( \partial H / \partial t = \Delta H (x, y) \). Filtering is performed as follows: a data set is formed in the form of a cross from 9 elements of the specified fields – 4 along the axis \( ox \), 4 along the axis \( oy \).
$OY$, and one in the center. The average value of 9 analyzed field elements is assigned to the central element and, thus, anomalously large and small values caused by errors are excluded. The cross-shaped filter area moves across the entire field. Since in this case the extreme data series are lost, it is necessary to take this into account when specifying the computational domain. Data correction is performed at specified time intervals, during which soil erosion is insignificant (usually, it is one hour) to take into account the effect of local bottom slopes on the critical values of Schilds numbers and critical bottom slope angles.

3. The structure of the software

The software for calculating the dynamics of the seabed, developed in C#, includes two modules: the initial data module (module 1) and the calculation module (module 2). Module 1 reads and processes the initial data required to calculate the deformation of the seabed surface.

Module 2 (calculation module) consists of calculating the specific soil transport over an uneven bottom and calculating the change in the bottom topography near the installation. As a result of the calculations, a file is created with the geometry of the seabed, taking into account the formed local washings and erosion for a given time interval. The resulting bottom geometry is exported to “CosmosFloWorks” for further hydrodynamic calculations taking into account the changed bottom geometry, i.e. with changed boundary conditions. After that, the results of calculating the flow velocity field are again entered into the program to calculate the change in the bottom geometry. Such a procedure is performed either during a given time interval or until the formed local washings and washings acquire a steady-state form, i.e. their changes during subsequent iterations will be insignificant. The structure of the program is shown in Fig. 1.

Figure 1. The structure of the program

The calculation of the dynamics of the bottom relief is performed for the time interval, which is determined in each specific case based on the achievement of a significant change in the bottom relief, which is several times larger than the grid step. Then, the change in the bottom structure is taken into account by setting new conditions at the bottom, taking into account the change in its structure. These changes are imported into COSMOSFloWorks. Then the boundary value problem is re-solved with new boundary conditions and the entire calculation of the depth change is repeated. Such repetitions are performed either until a steady state is reached, i.e. when the relative changes in depth will not
exceed a specified relative value, or before the expiration of a specified time interval, for example, the duration of a storm.

4. Result
In this section, we present the calculation of the flow and compare it with the results of the program.

The main algorithms of the program were used to perform numerical calculations 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.

The design diagram of the flow around the cylinder is shown in Figure 2.

Figure 2. The design scheme of flow around a vertical cylinder.

To solve a three-dimensional non-stationary problem, the dimensions of the computational domain are set along the axes, oy, oz, which is 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 is determined - the coordinates of its surface in the basic coordinate system. A sticking condition is set on a solid surface of a streamlined object; 2. On the boundary planes AA’CC’, ABCD and A’D’C’B’, a constant flow rate \( u_0 = U_0 \) (along the \( ox \) axis) is set; 3. At the boundary of the outgoing flow (plane BB’DD’), the Sommerfeld condition 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 \( l_p \) are specified [3]. 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 (\( l/D >>1 \)) and a cylinder of short aspect ratio (\( l/D = 1 \)).

Simulation of soil erosion near-vertical cylindrical support (\( D=1 \)) was carried out at a flow velocity of 0.65 m/s. The design depth is 10 m, \( \nu = 1.2 \cdot 10^{-6} \) m²/s, the type of soil is fine shell sand, taking into account the percentage of particles of various sizes (mm). The dimensions of the computational domain are -5 ... + 20 m along the \( ox \) axis, -5 ... + 5 m along the \( oy \) axis, and -10 ... 0 m along the \( oz \) axis. The physical time for calculating the steady-state flow was 30 s. A typical example of the results of calculating the velocity field and bottom surface topography near a vertical cylinder using the developed software is shown in Figure 3.
Figure 3. (a) The flow around a cylinder of finite length at Re = 10^6, (b) the changes in the structure and topography of the bottom surface in the form of a volumetric image.

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 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 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 ... 8 m from its center. The results obtained using the developed program completely coincide with manual calculations and correspond to the known results [3, 6, 7].

5. Conclusion
The effectiveness of the developed program is determined by the possibility of its use for predicting soil erosion under specific hydrodynamic conditions, parameters of the bottom material, and design features of the streamlined object. This is of great importance for preventing accidents associated with tilts and/or shifts of offshore drilling platforms, and also allows you to determine the moments of monitoring the real state of the soil near the support base and to take various measures to increase the safety of the installation, if necessary. The results of the performed numerical calculations showed that the maximum amount of soil erosion can reach approximately 1 ... 1.5 m at a stationary flow. In real conditions, the flow is variable. The developed system makes it possible to take into account such variations by assimilating the current data on the current velocity with the intervals of making the corresponding measurements, including based on remote sensing data. Moreover, at each such step, the problem is solved with the boundary conditions at the bottom that were obtained in the previous calculation.

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