Calculation of coast-protecting structure from wave influence

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Abstract. A coupled system consisting of a shore protection structure, a soil base and an aquatic environment is considered. The influence of the aquatic environment on the oscillations of the structure was taken into account. The wave processes arising in the system from the action of surfacing and breaking waves were investigated. The developed methodology and software package allow the calculation of various structures interacting with a deformable soil environment from the action of static and dynamic loads, taking into account the real properties of their materials, such as elasticity, viscosity and plasticity. The theory of plastic flow was used. Discretization of the computational area was performed by the finite element method. Studies were carried out on the basis of the obtained schemes of plastic zones, diagrams of stresses and oscillations at various points of the structure.

1. Introduction
When calculating shore protection structures in the normative document [1], it is recommended that dynamic wave actions be replaced by a static load, which is to some extent justified for standing waves. But in the case of breaking and breaking waves, under the influence of which the structures in question are usually located, it is necessary to use dynamic calculation methods. The coastal protection structure together with the soil mass forms a connected system, which is an inertial elastoplastic model that takes into account the wave processes arising in it. The theory of plastic flow with hardening is used, based on the Mises maximum principle [2]. For a flexible or rigid structure, the Geniev condition [3] is applied as a function of loading, and the Coulomb-Mohr condition [4] for soil.

2. Formulation of the problem
The technique for solving elastoplastic problems under dynamic loading in the above formulation is described in [5], therefore, here we present only the basic equations.

The equation of motion of the system at a time is found from the ratio of the principle of virtual work, which has the following form

\[
\int_\Omega \left[ \frac{\partial \varepsilon^T}{\partial u} \sigma d\Omega + \int_{\Omega} \left[ \frac{\partial \mu^T}{\partial \varepsilon} \right] \left( \rho \ddot{u} + c \dot{u} - Q \right) d\Omega - \int_{\Omega} \left[ \frac{\partial \mu^T}{\partial \varepsilon} \right] q d\varepsilon = 0. \]  \tag{1}
\]

It is believed that deformations of the system occur at small elongations, shifts, and rotation angles. Therefore, the relationship between the increments of displacements and deformations is determined by linear Cauchy relations

\[
d\varepsilon_{ks} = \frac{1}{2} \left( du_{k,s} + du_{s,k} \right). \tag{2}
\]

In this case, the postulate of summing the increments of elastic and plastic deformation also holds.

\[
d\varepsilon_{ks} = d\varepsilon_{ks}^{(e)} + d\varepsilon_{ks}^{(p)}. \tag{3}
\]

The components of the tensor of increments of elastic strain are related to the components of the tensor of increments of stress Hooke's law.
\[ d\varepsilon_{ks}^{(e)} = C_{ks}^{(e)} d\sigma_{mn}, \]

The increments of plastic deformations are defined as
\[ d\varepsilon_{ks}^{(p)} = d\lambda f_{\rho}, \quad d\lambda = \text{const} > 0. \]

The Genius condition in invariant form can be written as follows
\[ f = 3(\sigma_i - \sigma_p)\sigma_0 + 3\sigma_i^2 - \sigma_p\sigma_e = 0. \]

The Coulomb-Moore condition is written as
\[ f = \left(\sigma_0 - \frac{\sigma_i}{\sqrt{3}}\sin\psi\right)\sin\varphi + \sigma_i\cos\psi - c\cos\varphi = 0. \]

where, \(\sigma_0, \sigma_i, \sigma_p, \sigma_e, \varphi, c\) – are invariants of the stress tensor; \(\sigma_p, \sigma_e\) – plasticity limits under tension and compression; \(\varphi, c\) – angle of internal friction and adhesion.

Derivatives of the loading function are given in [5]. Transforming equations (3) \(\div (7)\), we find the equations of state:
\[ d\sigma_{ks} = D_{ks}^{(e)} d\varepsilon_{mn}, \quad \text{at} \quad f = 0, \quad df \leq 0 \quad \text{or} \quad f < 0; \]
\[ d\sigma_{ks} = D_{ks}^{(op)} d\varepsilon_{mn}, \quad \text{at} \quad f = 0, \quad df > 0. \]

The above initial equations have a complex form and can only be solved by numerical methods. This work uses direct step-by-step procedures. For their implementation, it is necessary to perform two main stages: discretization of the initial equations both in time and in the area occupied by the system; building an iterative process to determine a solution with a predetermined accuracy.

For the first discretization, the given time interval \([0, T]\) on which the solution is determined is divided into \(N\) time intervals of length \(\Delta t\) and the source equations are considered at each discrete time \(t_n\) instant. For the second discretization, the region of the system is divided by computers according to a special program into finite ones, and along infinite boundary of the soil massif into infinite isoparametric elements. If the array is limited to a finite region, then the waves reflected from its boundary can distort the results of the solution. After discretization at the moment of time \(t_n\) the following matrix equation is obtained
\[ M\ddot{\delta}_n + C\dot{\delta}_n + K(\delta)\delta_n = Q_n. \]

Here: \(M\) – matrix of distributed masses of the system; \(C\) – damping matrix; \(K(\delta)\) – non-linear stiffness matrix; \(Q_n\) – vector of nodal loads; \(\delta_n, \dot{\delta}_n, \ddot{\delta}_n\) – respectively, nodal displacements, speeds and accelerations.

An iterative process is constructed to determine the solution, which is implemented using the implicit modified Newmark method. It is unconditionally stable, which makes it possible to increase the length of the time step \(\Delta t\). The modification of the method is caused by the nonlinearity of elastoplastic problems and is described in detail in [5].

3. The main material and results
Based on the proposed methodology, a software package was developed in the Delphi system that allows numerically implementing various dynamic tasks. Usually, before a dynamic load is applied to a system, a static load acts on it, from which plastic zones form in some areas. Therefore, it is not possible, as is done in elastic calculation, to separately perform static and dynamic calculations and
summarize the results, since the principle of superposition is not applicable here. It is necessary to perform a joint calculation of the system from the action of both static and dynamic loads. The software package allows such a calculation.

Consider the solution to the problem, the design scheme of which is shown in Fig. 1. The shore protection wall of the corner type is under the action of breaking waves.

![Figure 1. The design scheme of the system.](image)

The following geometric dimensions of the structure were used in the calculation: \( h_1 = 9.5 \text{ m}; h_2 = 0.5 \text{ m}; l_1 = 1.0 \text{ m}; l_2 = 4.0 \text{ m}. \) Wave load: \( q_1 = 0.075 \text{ MPa}; q_1' = 0.017 \text{ MPa}. \) Characteristics of concrete walls: \( E_c = 300000 \text{ MPa}; \mu = 0.2; \sigma_0 = 1.8 \text{ MPa}; \sigma_c = 18 \text{ MPa}. \) Soil properties: \( E_0 = 40 \text{ MPa}; \mu = 0.3; c = 0.01 \text{ MPa}; \varphi = 26^\circ. \) The length of the time step \( \Delta t = 0.001 \text{ sec.} \), The duration of the load 0.1 sec. The solution is determined on the time interval \( T = 3 \text{ sec.} \)

First, a static calculation is performed on the effect of the dead weight of the wall and backfill. From this load point A, shown in Fig. 1, receive displacements \( u_1 = -1.242 \text{ cm}, u_2 = -4.456 \text{ cm}. \) Plastic zones form in the soil mass. Then, taking into account the stress-strain state determined from the action of its own weight, a dynamic calculation was performed from the action of the wave load. In Fig. 2 shows the plastic zones that formed in the soil mass from both loads at time \( t = 0.48 \text{ sec.} \) On the display screen during the oscillation of the system, it is possible to observe the formation of new plastic zones and the closure of those that arose earlier, and the plastic regions that formed after the static calculation go into the elastic stage. Consequently, the system is under complex loading, therefore, deformation plasticity theories cannot be applied to such problems.

In Fig. 3 shows a plot of the time variation of stress \( \sigma_{22} \) at point B shown in Fig. 1. At this point, from the action of a static load, a voltage of \( -0.072 \text{ MPa} \) arises. On the time interval \( T = [0, 3] \text{ sec.} \) loading occurs, which lasts 0.1 seconds. and free vibrations taking up the rest of the time. During loading, compressive stresses \( \sigma_{22} \) vary to \( -0.078 \text{ MPa}. \) Then, at the stage of free oscillations, unstable voltage fluctuations arise for 0.45 seconds, which then stabilize and decay.

In Fig. 4 and Fig. 5 shows the diagrams of the horizontal and vertical oscillations of point A. After the action of the static load, the horizontal movements occur in a sharp jump in the direction of the wave load and at \( t = 0.16 \text{ sec.} \) reach a value of 0.979 cm. Then this point moves in the opposite direction and then it oscillates around a position equal to \( -1.5 \text{ cm}. \) It should be noted that such oscillations do not occur near a static equilibrium position of \( -1.242 \text{ cm}, \) but this position has shifted, caused by the formation of plastic deformations. The same picture is observed for vertical vibrations. In the initial period of free oscillations, point A moves up to \( u_2 = -4.1 \text{ cm}, \) then its oscillations occur near a position equal to \( u_2 = -4.54 \text{ cm}, \) which is not equal to the static \( u_2 = -4.456 \text{ cm}. \)
Figure 2. The formation of plastic zones in the system at time $t = 0.48$ sec.

Figure 3. Diagrams of stress $\sigma_{22}$ at point $B$ (at 10 MPa).
4. Findings

In conclusion, it should be noted that the proposed methodology and software package make it possible to calculate shore protection structures from the combined action of static and dynamic loads, taking into account the occurrence of plastic zones both in the structure and in the soil mass. When solving dynamic problems, it is necessary to take into account the deformations and stresses obtained from static loads, since they affect the oscillatory process that occurs when the system is dynamically
loaded. In addition, the wall and soil environment are interconnected. The change in time of the properties of one element of the system affects the stress-strain state of another. Therefore, only their joint calculation will allow to obtain the correct results.

References
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