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THEORETICAL INVESTIGATION OF THE EFFECT OF WIND WAVES ON EROSION PROCESSES IN COHESIVE-SOIL CHANNELS

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ABSTRACT

The paper presents the results of a theoretical investigation of erosion processes in cohesive soils forming the beds of open channels under the influence of wind-generated waves. The relevance of the study is associated with the need to ensure the stability and reliability of channels composed of cohesive soils under the combined effects of hydraulic flow and wind-induced wave action. The stability conditions of cohesive soils are considered, and the forces acting on an individual soil aggregate within the near-bed flow region are analyzed, taking into account the additional hydrodynamic effects generated by wind waves. In the proposed calculation model, cohesive soil is represented as a system of interconnected aggregates whose stability is governed by the cohesive forces between the aggregates and the channel bed, the submerged weight of the aggregate, and the hydrodynamic forces associated with wind-generated waves.

Using the limit-state approach, the critical condition of a cohesive-soil aggregate subjected to combined hydraulic and wind-wave action is established. The

analysis considers the frontal and lifting components of the hydraulic forces, the additional effects of wind-generated waves, the geometric characteristics of the soil aggregate, its resistance to tensile and bending effects, and the roughness characteristics of the channel bed. Theoretical relationships are derived for determining the erosive, non-erosive, and bottom non-erosive velocities of water flow in channels composed of cohesive soils under wind-wave action.

In determining the near-bed flow velocity, the logarithmic law of velocity distribution in the vicinity of the channel bed is taken into account together with the adopted value of absolute bed roughness. The influence of wind-generated waves on the near-bed hydrodynamic conditions and the resulting shear and lifting forces acting on cohesive-soil aggregates is also considered.

The proposed calculation approach is based on the principles of reliability theory and probabilistic assessment of the limit state of a soil aggregate. The resulting relationships make it possible to evaluate the stability of cohesive soils and determine the permissible hydraulic flow parameters under the combined influence of water flow and wind-generated waves, at which detachment and progressive erosion of soil aggregates from the channel bed do not occur. The obtained results can be applied to the hydraulic analysis and design of unlined channels, as well as to the assessment of the stability of channel beds composed of cohesive soils exposed to wind-wave action. However, the influence of the lateral slope of the channel and the detailed spatial characteristics of wind-generated waves are not considered in the derived relationships, although these factors may significantly affect the hydraulic characteristics of the flow and erosion intensity. Therefore, further research should focus on establishing the influence of the geometric parameters of trapezoidal channels, side slopes, and wind-wave characteristics on the non-erosive velocity of water flow and the stability of cohesive-soil channel beds..

Keywords: cohesive soil, channel erosion, open channel, wind-generated waves, wind-wave action, non-erosive velocity, erosive velocity, limit state, hydrodynamic force, near-bed velocity, channel roughness, soil stability, wave-induced hydrodynamic forces.

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**ТЕОРЕТИЧЕСКОЕ ИССЛЕДОВАНИЕ ВЛИЯНИЯ ВЕТРОВЫХ
ВОЛН НА ЭРОЗИОННЫЕ ПРОЦЕССЫ В РУСЛАХ СО СВЯЗНЫМИ
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АННОТАЦИЯ

В статье представлены результаты теоретического исследования процессов эрозии связных грунтов, формирующих русла открытых каналов, под воздействием волн, возникающих в результате действия ветра. Актуальность исследования обусловлена необходимостью обеспечения устойчивости и надежности каналов, сложенных связными грунтами, при совместном воздействии водного потока и ветрового волнения. Рассмотрены условия устойчивости связных грунтов и проанализированы силы, действующие на отдельный агрегат грунта в придонной области потока с учетом дополнительных гидродинамических воздействий, возникающих под действием ветровых волн. В предлагаемой расчетной модели связный грунт представлен как система взаимосвязанных агрегатов, устойчивость которых определяется силами сцепления между агрегатами и дном канала, взвешенным

весом агрегата, а также гидродинамическими силами, связанными с воздействием ветровых волн.

С использованием подхода предельного состояния установлено критическое условие устойчивости агрегата связного грунта при совместном воздействии водного потока и ветровых волн. При анализе учитываются лобовая и подъемная составляющие гидродинамических сил, дополнительные воздействия, обусловленные ветровыми волнами, геометрические характеристики грунтового агрегата, его сопротивление растягивающим и изгибающим воздействиям, а также характеристики шероховатости дна канала. Получены теоретические зависимости для определения размывающей, неразмывающей и донной неразмывающей скоростей водного потока в каналах, сложенных связными грунтами, с учетом воздействия ветровых волн.

При определении придонной скорости потока учитывается логарифмический закон распределения скорости вблизи дна канала совместно с принятой величиной абсолютной шероховатости дна. Также учитывается влияние ветровых волн на гидродинамические условия в придонной области и возникающие в результате этого касательные и подъемные силы, действующие на агрегаты связного грунта.

Предлагаемый расчетный подход основан на принципах теории надежности и вероятностной оценки предельного состояния грунтового агрегата. Полученные зависимости позволяют оценить устойчивость связных грунтов и определить допустимые гидравлические параметры потока при совместном воздействии водного потока и ветровых волн, при которых не происходит отрыва и прогрессирующего размыва агрегатов грунта от дна канала. Полученные результаты могут быть использованы при гидравлических расчетах и проектировании каналов с неукрепленным руслом, а также при оценке устойчивости русел, сложенных связными грунтами и подверженных воздействию ветрового волнения. Вместе с тем в полученных зависимостях не учитываются влияние боковых откосов канала и детальные пространственные характеристики волн, возникающих под воздействием ветра, хотя данные факторы могут существенно влиять на гидравлические характеристики потока и интенсивность эрозионных процессов. Поэтому дальнейшие исследования должны быть направлены на установление влияния геометрических параметров трапецидальных каналов, заложения боковых откосов и характеристик ветровых волн на неразмывающую скорость водного потока и устойчивость русел каналов, сложенных связными грунтами.

Ключевые слова: связный грунт, эрозия русла, открытый канал, ветровые волны, воздействие ветровых волн, неразмывающая скорость, размывающая скорость, предельное состояние, гидродинамическая сила, придонная скорость, шероховатость русла, устойчивость грунта, волновые гидродинамические силы.

A number of researchers have proposed methods for calculating hydraulic structures based on the limit-state approach [1,2]. These methods are based on various considerations concerning the causes of structural failure and the safety and reliability of hydraulic structures. In particular, emphasis is placed on the statistical evaluation of parameters characterizing structural performance, which is one of the principal factors in determining safe structural dimensions. In the case of open channels composed of cohesive soils, the assessment of stability should also account for the additional hydrodynamic effects caused by wind-generated waves, which can increase the shear and lifting forces acting on the channel bed and accelerate erosion processes.

Using the limit-state method, we consider a procedure for determining the critical flow velocity above which cohesive soils are eroded under the combined action of water flow and wind-generated waves. The proposed approach makes it possible to evaluate the stability of cohesive-soil aggregates by considering both the hydrodynamic forces generated by the flowing water and the additional wave-induced forces resulting from wind action. This provides a more comprehensive assessment of the conditions leading to the detachment and erosion of cohesive-soil particles from the channel bed.

We assume that water-saturated cohesive soil, similarly to non-cohesive soil, consists of individual spherical particles d of a certain diameter. However, in cohesive soils, individual particles form aggregates bonded to one another by cohesive forces. These aggregates are characterized by a high equivalent fictitious γ_e specific weight, which represents the force required to detach a particle from the soil and is equal to the detachment force of a cohesive-soil aggregate.

Under the combined action of water flow and wind-generated waves, the stability of cohesive-soil aggregates is affected by both the mean hydrodynamic forces of the flowing water and the additional oscillatory forces induced by wind waves. These wave-induced forces can increase the shear and lifting effects acting on the channel bed and, consequently, contribute to the detachment and erosion of cohesive-soil aggregates. Therefore, the assessment of aggregate stability should take into account the combined hydraulic and wind-wave action.

The dimensions of the aggregates that can be detached under the combined action of water flow and wind-generated waves can be estimated in the calculations using the following absolute roughness height:

$$\Delta = 0,7d, \quad (1)$$

where d - the aggregate diameter.

One of the main soil characteristics determining resistance to channel erosion is cohesion. Therefore, this property is taken into account in modeling cohesive soils.

The cohesion force corresponding to one cohesive-soil aggregate under dynamic loading is given by the following expression:

$$R_{co} = C_y^n d^2, \quad (2)$$

where C_y^n - the fatigue limit of cohesive-soil failure,

$$C_y^n = 0,035C \quad (3)$$

is determined from the following expression. Here, C - the cohesion in the water-saturated state.

In addition to overcoming the cohesion force, detaching a cohesive-soil aggregate also requires overcoming the submerged weight of the soil:

$$R_{ce} = (\gamma_s - \gamma) \frac{\pi d^3}{6}. \quad (4)$$

For a non-cohesive soil particle of diameter d to be detached from the bed, a force equal to the weight of the particle is required, which can be expressed as follows:

$$R_{ne} = (\gamma_s - \gamma) \frac{\pi d^3}{6}, \quad (5)$$

where γ_s and γ - the specific weights of the soil and water particles, respectively.

The resistance to detaching a particle having an equivalent fictitious specific weight is as follows: γ_e having an equivalent fictitious specific weight, the resistance to detachment from the bed is given by:

$$R_{ne} = (\gamma_e - \gamma) \frac{\pi d^3}{6}. \quad (6)$$

Thus, the resistance to detaching a particle having an equivalent fictitious specific weight from the bed can be expressed as follows: γ_e having an equivalent fictitious specific weight, we express the resistance to detachment from the bed as follows:

$$R_{ne} = R_{ce} + R_{co} \quad (7)$$

or

$$(\gamma_s - \gamma) \frac{\pi d^3}{6} = (\gamma_u - \gamma) \frac{\pi d^3}{6} + C_y'' d^2. \quad (8)$$

From this equality, we obtain the following:

$$\gamma_s = \gamma_u + \frac{6C_y''}{\pi d}. \quad (9)$$

The aggregate located on the channel bed is subjected to P_x frontal and P_z lifting forces exerted by the flow (see Fig. 1). In this case, the P_x frontal force tends to move the aggregate in the direction of flow, while the P_z lifting force tends to detach the aggregate from the bed and move it vertically upward [5].

The soil strength condition is that, at the limiting state, the forces acting on a cohesive-soil aggregate are balanced by the adhesion forces between the aggregates and the underlying bed, together with the weight of the aggregate.

The forces acting on the aggregate produce an eccentric stress distribution.

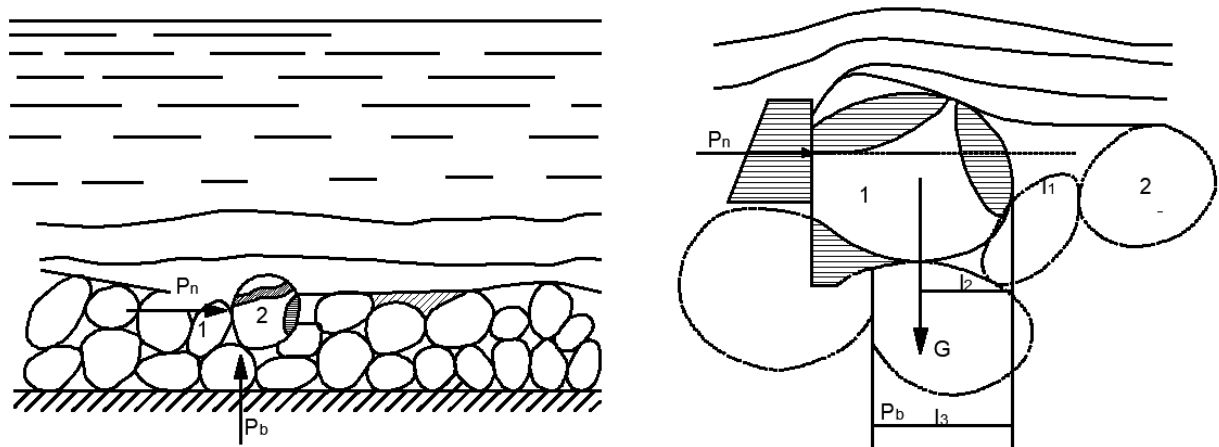


Fig. 1. Schematic diagram of the forces acting on a cohesive-soil aggregate under flow action

The limiting state of a cohesive-soil aggregate is expressed as follows:

$$n \left(\frac{P_y}{m_p F} + \frac{P_x \delta_1 d}{m_u W} \right) \leq C_{pc} + \frac{G_B}{F}, \quad (10)$$

where m_p , m_u - the coefficients characterizing the tensile and bending working conditions of the aggregate; in the calculation, $m_p = m_u = m$ is assumed; $n = (u_{\Delta \max} / \bar{u}_{\Delta})^2$ - a load factor accounting for the pulsating nature of the flow velocity and, consequently, possible excess loads (stresses) exceeding their calculated values. In this case, $u_{\Delta \max}$ and $\bar{u}_{\Delta}$ are the instantaneous maximum and time-averaged near-bed

velocities corresponding to the roughness height. If $d < 0,001\text{ m}$ is the case, the stress factor is determined from the following

$$n = 1 + \frac{d}{0,00005 + 0,3d} \quad (11)$$

is determined from the formula; when $d > 0,001\text{ m}$ applies, it may be assumed that $n = 4$; C_p - the calculated resistance of the cohesive soil, which is lower than its tensile strength capacity; G_s - the submerged weight of the aggregate; F - the area of the aggregate bearing surface; w - the resistance moment of the bearing section;

The resultant frontal force is expressed as follows:

$$P_x = \gamma_o \gamma_x \frac{v_\Delta^2}{2g} \delta_3 d^2; \quad (12)$$

The resultant lifting force is given by:

$$P_y = \gamma_o \gamma_y \frac{v_\Delta^2}{2g} \delta_3 d^2; \quad (13)$$

The submerged weight of the aggregate is:

$$G_B = \frac{\pi}{6} (\gamma_u - \gamma_o) d^3; \quad (14)$$

The area of the aggregate bearing surface is:

$$F = \frac{\pi}{4} (\delta_4 d)^2; \quad (15)$$

The resistance moment of the bearing section is:

$$W = 0.0982 (\delta_4 d)^3, \quad (16.)$$

where γ_u, γ_o - **the specific weights of the aggregate and water, respectively**;

$\delta_4 d$ - the diameter of the aggregate bearing section; $\delta_1 d$ - the frontal-force lever arm; $\delta_2 d^2; \delta_3 d^2$ - the midsection area of the frontal and lifting forces; λ_x, λ_y - the coefficients of the frontal and lifting forces, i.e. $\gamma_x = 0,40 - 0,45$ and $\lambda_y / \lambda_x = 0,25$.

Substituting the expressions and values given above into condition (10), we obtain:

$$C_{p.c} = C_y^H K = \frac{\gamma_o v_\Delta^2}{2g} \left[\frac{4\lambda_y \delta_3}{\pi \delta_4^2} + \frac{\lambda_x \delta_2 \delta_1}{0.0982 \delta_4^3} \right] - \frac{2 (\gamma_u - \gamma_o)}{3 \delta_4^2}. \quad (17)$$

From this equation, we determine the v_Δ flow velocity:

$$v_\Delta = \sqrt{\frac{2g}{\gamma_o \left(\frac{4\lambda_y \delta_3}{\pi \delta_4^2} + \frac{\lambda_x \delta_2 \delta_1}{0.0982 \delta_4^3} \right)}} \left[\frac{2}{3 \delta_4^2} (Y_u - Y_o) d + C_y^H K \right]. \quad (18)$$

Taking into account that the distribution of velocities in the near-bed zone follows a logarithmic law, the near-bed velocity can be expressed through the mean velocity as follows:

$$\frac{v_{\Delta}}{v} = \frac{\lg\left(\frac{16.7Y}{\Delta} + 1\right)}{\lg\left(\frac{6.15H}{\Delta}\right)} . \quad (19)$$

Assuming the roughness height to be $0,7d$ we obtain

$$v_{\Delta} = \frac{1.25v}{\lg\left(\frac{8.8H}{d}\right)} . \quad (20)$$

Based on the soil erosion process, we assume that when $K=1$ ($C_{p.c} = C_y^H K = C_y^H$) the flow velocity is erosive. At erosive velocity values, aggregates whose cohesion is less than or equal to the mean cohesion value are detached by the flow, resulting in widespread detachment of the cohesive-soil aggregates forming the channel bed.

Substituting expression (20) into relation (18), we obtain the following relationship for the erosive flow velocity in cohesive soils:

$$v_p = \left(\lg \frac{8,8H}{d}\right) \sqrt{\frac{2gm}{1,3\gamma_o n} [(\gamma_u - \gamma_o)d + 1, 25C_y^H]} . \quad (21)$$

Taking into account the relationship known from the dynamics of open channels, $v_p = 1,4v_u$ we obtain from relation (21) the relationship for determining the non-erosive flow velocity:

$$v_H = \left(\lg \frac{8,8H}{d}\right) \sqrt{\frac{2gm}{2,6\gamma_o n} [(\gamma_u - \gamma_o)d + 1, 25C_y^H K]} ; \quad (22)$$

$$v_{\Delta H} = 1,25 \sqrt{\frac{2gm}{2,6\gamma_o n} [(\gamma_u - \gamma_o)d + 1, 25C_y^H K]} . \quad (23)$$

Thus, the non-erosive flow velocities in channels composed of cohesive soils under the combined influence of water flow and wind-generated waves are determined using formulas (22)–(23). These relationships allow the critical hydraulic conditions to be evaluated by taking into account the additional hydrodynamic effects induced by wind-generated waves.

The proposed method is based on the principles of reliability theory and probability theory and, when compared with a large number of laboratory and field experiments, demonstrates reliable results. The consideration of wind-generated waves makes it possible to more adequately assess the stability of cohesive-soil channel beds under combined hydraulic and wave-induced loading.

However, the relationships (22)–(23) used to determine the non-erosive flow velocities do not fully account for the influence of the channel-side slope and the detailed characteristics of wind-generated waves, including wave height, period, and direction. These factors can significantly affect the structure of the flow, the distribution of near-bed velocities, and the magnitude of shear and lifting forces acting on cohesive-soil aggregates. Therefore, further studies are required to determine the combined influence of channel geometry, particularly the side slope of trapezoidal channels, and the characteristics of wind-generated waves on the non-erosive flow velocity and erosion resistance of cohesive-soil channel beds.

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