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Hydraulic Modeling of Dispersed Flow

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Abstract: This study focuses on evaluating the operational conditions of supply channels within irrigation system pumping stations, with a particular emphasis on those associated with the Karshi main canal. The primary objective is to devise new approaches to optimize the functioning of key components in order to achieve energy-efficient operations. Through the integration of innovative elements into irrigation systems during refurbishment, the study aims to diminish hydraulic losses per unit power of pumping units, resulting in additional energy savings and reduced technological costs. The significance of the research findings lies in the development of an original expression of the Stokes criterion, which aids in characterizing the behavior of multiphase water flows interacting with clay sediment particles on solid surfaces, such as those present in coastal protection structures. A hydraulic model has been devised to illustrate the dynamics of dispersed water flow interacting with solid surfaces, thereby providing valuable insights into the intricate processes involved..

Keywords: Hydraulic model, clay sediments, water flow, density, solid surface, dispersed flow

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1. Introduction

In the realm of hydraulic modeling within supply channels, it becomes crucial to comprehend the behavior of a two-phase (dispersed) water flow as it interacts with the rocky surfaces of coastal protective structures. Field research findings, analyzed by experts, reveal that during the months of June and July, the turbidity of water flow typically ranges between 3.3 to 10.0 kg/m3, with a fractional composition of turbid effluents spanning 0.05 mm. This turbidity, attributed to the movement of solid clay particles within the water flow, leads to erosion of the sturdy rock and concrete surfaces constituting the coastal protection structures. Consequently, the stability of these structures is compromised, as they succumb to erosion and fall into disrepair.

The Subject and Methodology of the Study

Within the context of the interaction between moving dispersed waters and solid surfaces (components of coastal protection structures), understanding the inertial characteristics of turbid sediment particles and solid surface particles becomes paramount. The primary parameter delineating the inertia of these particles is the Stokes criterion.

The Stokes similarity criterion (Stk) elucidates the interaction between turbid particles within a moving dispersed liquid and the particles present on the surface of solid bodies that impede the water flow. In essence, the Stokes criterion captures the dynamics of turbid particle velocities within dispersed water and the phenomenon of relaxation in close proximity to interacting solid surfaces.

To effectively articulate the crucial aspects of multiphase water flow dynamics during interactions with water streams, clay sediment particles, and solid surfaces (components of coastal protection structures), a novel expression for the Stokes criterion is essential. This endeavor utilizes the formulaic methods of continuum mechanics and delves into the study of a multiphase continuum.

The multiphase continuum is characterized by density (ϱ_i) and velocity (v_i) at arbitrary points within the neighboring medium. Utilizing these parameters, the state and behavior of dispersed liquids can be comprehensively understood, as outlined in prior literature [1,2].

$$\rho = \sum_{i=1}^{N} \rho_i \ , \ \ \rho\vartheta = \sum_{i=1}^{N} \rho_i \, \vartheta_i \tag{1}$$

In many instances, the state and motion of dispersed liquids, along with the velocities of mixture components, are also articulated in terms of wi

$$W_i = \vartheta_i - \vartheta, \ \sum_{i=1}^{N} \rho_i \, W_1 = 0 \tag{2}$$

Now we introduce substantial derivatives for a multiphase continuum:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \vartheta \cdot \nabla = \frac{\partial}{\partial t} + \vartheta^k \cdot \nabla^k = \frac{\partial}{\partial t} + \vartheta^k \frac{\partial}{\partial x^k} \tag{3}$$

where: k is the index corresponding to the coordinate axes.

The laws governing the motion of dispersed liquids are derived from the principles of conservation of mass, momentum, and energy. Thus, by applying the law of conservation of mass to depict the interaction between a volume W of water flow and particles of a solid surface S, the following equation is formulated [1,2]:

$$\int_\vartheta \frac{\partial \rho_i}{\partial t} dV = -\int_s \rho_i \vartheta_i^n \, ds + \int_V \sum_{\substack{j=1 \\ j \neq i}}^{N} J_{ji} \cdot dV, \quad \text{(i=1,2,…N)} \tag{4}$$

where Jji represents the mass transfer within a dispersed liquid per unit volume [kg/(m³ s)]. If we assume Jii=0 under various physical and mechanical spatial intensities, then the following equality holds:

Jji=–Jij (5)

To conduct subsequent mathematical operations, we employ the Gauss-Ostrogradsky formula.

$$\int_s A\vartheta \cdot n ds = \int_V \nabla^k A \vartheta^k dV$$

Using the Gauss-Ostrogradsky formula, we obtain the following equation for each component (4) of a dispersed liquid:

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot \rho_i \vartheta_i = \sum_{j=1}^{N} j_{ji} \ \text{(i=1,2,…N)} \tag{6}$$

$$\text{Or} \ \frac{\partial \rho_i}{\partial t} + \nabla \cdot \rho_i (\vartheta + W_i) = \sum_{j=1}^{N} j_{ji} \ \text{(i=1,2,…N)} \tag{7}$$

When a single-component liquid moves, we obtain a simple equation of diffusion motion from equations (6) and (7):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho\vartheta = 0 \tag{8}$$

If we take into account that two-phase (water, turbid precipitation) motion is studied within the framework of the article, then the system of equations (6) will have the following form:

$$\begin{aligned} \frac{\partial \rho_1}{\partial t} + \frac{\partial \rho_1 \vartheta_1^k}{\partial x^k} &= nj_{21} \, , \\ \frac{\partial \rho_2}{\partial t} + \frac{\partial \rho_2 \vartheta_2^k}{\partial x^2} &= nj_{12,} \\ \frac{\partial n}{\partial t} + \frac{\partial n \vartheta_2^k}{\partial x^k} &= 0 \end{aligned} \tag{9}$$

Where n represents the concentration of turbid sediment particles in a dispersed mixture per unit volume.

Considering the radial velocities wi of constituent phases C1 and C2, which denote the volume concentrations of the first and second phases respectively, and incorporating the expressions with $C_1 + C_2 = 1, C_2 = \frac{4}{3}\pi a^3 n$ along with $\rho_1 = \rho_1^0 C_1, \rho_2 = \rho_2^0 C_2$ and $\rho = \rho_1 + \rho_2$ for the displacement of dispersed water and a solid surface (coastal elements of a protective structure), we derive the equation of conservation of mass at the interface:

$$\rho_1^0(\omega_1 - \dot{a}) = \rho_2^0(\omega_2 - \dot{a}) = \frac{j_{21}}{4\pi a^2};\ \dot{a} = \frac{da}{dt} \qquad (10)$$

Using the mass conservation equation (10), we derive equations that describe the phase density of adjacent media, the volume concentration of turbid sediment particles, and the change in velocity of suspended particles at the boundary between dispersed water and the surface of a solid body (components of a coastal protection structure):

$$C_1\frac{d_1\rho_1^0}{dt} + \rho_1^0\frac{d_1 C_1}{dt} = nj_{21} - \rho_1^0 C_1\frac{Dv_1^k}{Dx^k}$$

$$C_2\frac{d_2\rho_2^0}{dt} + \rho_2^0\frac{d_2 C_2}{dt} = nj_{12} - \rho_2^0 C_2\frac{Dv_2^k}{Dx^k}$$

$$\frac{d_2 C_2}{dt} = \frac{d_2}{dt}\left(\frac{4}{3}\pi a^3 n\right) = \frac{4}{3}\pi a^3\frac{d_2 n}{dt} = 4\pi a^2\frac{d_2 a}{dt} = -\alpha_2\frac{Dv_2^k}{Dx^k} + \frac{3x_2}{a}\frac{d_2 a}{dt}$$

equation (5.10) is written for $-j_{ji}$:

$$\left.\begin{aligned} &C_1\frac{d_1\rho_1^0}{dt} = -\rho_1^0\frac{D}{Dk^k}\left(C_1 v_1^k + C_2 v_2^k\right) + \frac{3C_1\omega_1}{a}\rho_1^0,\\ &C_2\frac{d_2\rho_2^0}{dt} = -\frac{3C_2\omega_2}{a}\rho_2^0,\\ &\frac{d_2 C_2}{dt} - \frac{3C_2}{a}\frac{d_2 a}{dt} = -C_2\frac{Dv_2^k}{Dx^k},\\ &\frac{d_2 a}{dt} = \omega_1 - \frac{j_{21}}{4\pi a^2\rho_1^0} = \omega_1 - \frac{j_{12}}{4\pi a^2\rho_2^0} \end{aligned}\right\} \qquad (11)$$

The research findings reveal a new expression for the Stokes criterion, achieved by representing the forces acting on particles of a solid surface (components of a coastal protection structure) due to the dispersed flow of water through the following equations:

$$\left.\begin{aligned} F&=F_1+F_*\\ F_*&=F_2+F_3 \end{aligned}\right\} \qquad (12)$$

where: F is the sum of forces acting on a solid surface (elements of a coastal protection structure) with dispersed water, F_1 is the force of hydrostatic pressure, F_2 is the friction force, F_3 *is* the force acting on particles of the surface of a solid from the side of particles of a turbid liquid in a dispersed water mixture (force in the direction opposite to the shear force acting on particles of the solid surface), λ is the coefficient of hydraulic friction.

We define the forces in the system of equations (12) by the following expressions [2]:

$$\left.\begin{aligned} &F = \frac{4\pi\cdot a^3}{3}\rho_1^0\left(\frac{dw_{12}}{dt} - g\right), F_1 = \frac{4\pi\cdot a^3}{3}\rho_1^0\left(\frac{dV_1}{dt} - g\right)\\ &F_2 = C_\mu \pi a^2\frac{\rho_1^0\omega_{12}^2}{2}\frac{W_{12}}{\omega_{12}},\\ &F_3 = \frac{2\pi\cdot a^3}{3}\rho_1^0\left(\frac{dV_1}{dt} - \frac{dV_2}{dt} + \frac{3}{a}\frac{da}{dt}w_{12}\right),\\ &C_\mu = C_\mu(R_e, C_2)\ \text{ёки}\ C_\mu = Stk = \lambda\psi\\ &R_e = \frac{2a\rho_1^0 W_{12}}{\mu},\\ &W_{12} = V_1 - V_2 \end{aligned}\right\} \qquad (13)$$

where: C_μ is a dimensionless coefficient or Stokes number characterizing the resistance to the flow of particles on a solid surface under the influence of a dispersed flow, a is the displacement of the shore protection elements under the influence of a dispersed water flow [cm].

Considering the system of equations (12) and (13), we obtain the following equation:

$$\frac{dV_2}{dt} = \frac{3}{4}C_\mu\frac{\omega_{12}}{a}\cdot W_{12} + \frac{dV_1}{dt} + \frac{3}{a}\frac{da}{dt}W_{12} \qquad (14)$$

Conclusion

1. We have successfully developed a new expression for the Stokes criterion, which enables the characterization of crucial aspects of multiphase water flow dynamics during interactions with clay sediment particles and solid surfaces (components of a coastal protective structure) within the water stream.
2. Additionally, a hydraulic model has been devised to accurately portray the dynamics of dispersed water flow as it interacts with solid surfaces.

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