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HYDRODYNAMIC METHODOLOGICAL FOUNDATIONS FOR IDENTIFYING DEFORMATION PROCESSES IN THE INFLOW CHANNEL OF THE OQTEPA RESERVOIR

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Abstract

This article provides a theoretical analysis of the hydrodynamic methodological principles for identifying deformation processes occurring in the inlet channel of the Oktepa Reservoir. A hydrodynamic modeling approach is proposed based on the interaction between flow velocity, pressure distribution, and soil structure. The model evaluates soil shear potential through variations in flow velocity and pressure gradient. The research results make it possible to predict hazardous hydraulic conditions leading to deformation in the reservoir's inlet zone. The proposed methodological approach has significant practical importance for ensuring the operational safety of hydraulic structures.

Keywords: reservoir, inlet channel, deformation process, hydrodynamic model, soil stability, flow velocity.

Introduction

In recent years, deformation processes occurring during the operational period of hydraulic structures—particularly in the inflow channels of reservoirs—have been identified as a widespread problem on both global and regional scales. Such processes arise as a result of uneven flow-velocity profiles, variations in channel geometry, and complex interactions between the soil and structural components [1]. Deformations not only compromise the structural stability but also directly and adversely affect the reliability and efficiency of the water supply system—thereby imposing new requirements on water resource management strategies [2].

Local velocity and pressure gradients of the flow impact the channel bed and walls, promoting processes such as scouring, displacement, subsidence, and erosion. In particular, the mechanical properties of stratified soils (e.g., density, internal friction angle, and porosity) and their alterations under the influence of water determine the mechanism of deformation development [3]. Various flow regimes along the channel—laminar, sharp bends, or turbulence zones formed at turns—modify stresses and moments of rotation associated with bed materials, leading to localized deformations [4].

Given that the Oqtepa Reservoir plays an important role in the water distribution system of the Republic, and that the hydrodynamic condition of its inflow channel is directly linked to the overall safety of the system, developing a predictive methodology to ensure channel stability becomes a critical research objective [5]. Even small initial defects in the channel structure can lead to substantial material losses through prolonged interaction with the flow, indicating the necessity of a scientifically grounded approach combining monitoring and forecasting methods [6].

The approach proposed in this paper is a theoretical model based on hydrodynamic analysis, which aims to integrate the mathematical description of the flow field, the deformational behavior of the soil, and its interaction with the channel surface. Through this model, the distribution of energy along the channel, pressure and velocity gradients, as well as plastic and elastic deformations occurring within soil layers are evaluated [7]. Furthermore, the model allows for the calibration of parameters based on theoretical and experimental data, enabling the early detection of deformation processes and the quantitative assessment of risk levels under real conditions [8].

The scientific results can be applied in planning construction and repair operations, developing technical measures to mitigate erosion risks, and optimizing long-term monitoring systems. Implementing this approach in practice is aimed at enhancing the stability and service life of the Oqtepa Reservoir inflow channel, as well as improving the reliability of the regional water supply system [9].

Research Methods

The study was conducted based on the principles of hydrodynamic modeling. This approach allows for analyzing the flow processes along the channel, the impact on soil layers, and the identification of potential deformation risk zones [1]. The model was developed using a deterministic mathematical framework,

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describing the relative balance between flow velocity, pressure gradient, and the internal resistance forces of the soil [2].

Fundamental Assumptions

The model relies on the following scientific assumptions:

Flow regime — The water movement along the channel can occur under a stable laminar or transitional turbulent regime, as the cross-section of the inlet channel remains constant, while the velocity profile is naturally uneven [3, p.518].

Mechanical behavior of the soil — The soil shear limit is determined based on the Mohr–Coulomb model:

$$\tau = c + \sigma \tan \varphi$$

where: τ – shear resistance (Pa), c – cohesion (Pa), σ – normal stress (Pa), φ – internal friction angle (°) [4].

Deformation probability (Ψ) — evaluated as the ratio between the kinetic energy of the water flow and the internal resistance of the soil:

$$\Psi = \frac{\frac{1}{2}\rho v^2 + p}{\tau + \gamma h}$$

where: v – flow velocity (m/s); p – pressure (Pa); ρ – water density (kg/m³); τ – soil shear resistance (Pa); h – water depth (m); γ – unit weight of the soil (N/m³) [5].

If **Ψ > 1**, it indicates that the hydrodynamic energy of the flow exceeds the internal resistance of the soil, signifying a potential deformation risk. Under such conditions, processes such as erosion, subsidence, or shear may occur along the channel bed or walls [6].

Mathematical Model Scheme

Figure 1 presents the **hydrodynamic modeling scheme** of the Oqtepa Reservoir inflow channel. The diagram illustrates the **flow velocity vectors, pressure gradients**, and **shear zones** occurring between the soil layers.

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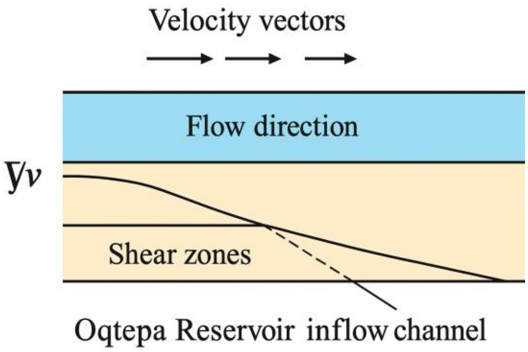

Figure 1. Hydrodynamic modeling scheme of the Oqtepa Reservoir inflow channel

Table of Flow Parameters and Soil Properties

Table 1. Modeled values of flow and soil parameters (source: based on author's calculations [2, 4, 6])

Parameter	Symbol	Unit of measurement	Value (Average)
Flow velocity	v	m/s	1.2 – 2.8
Pressure gradient	dp/dx	Pa/m	15 – 40
Water density	ρ	kg/m³	998
Soil shear resistance	τ	Pa	150 – 300
Water depth	h	m	2.0 – 3.5
Internal friction angle	φ	°	22 – 28

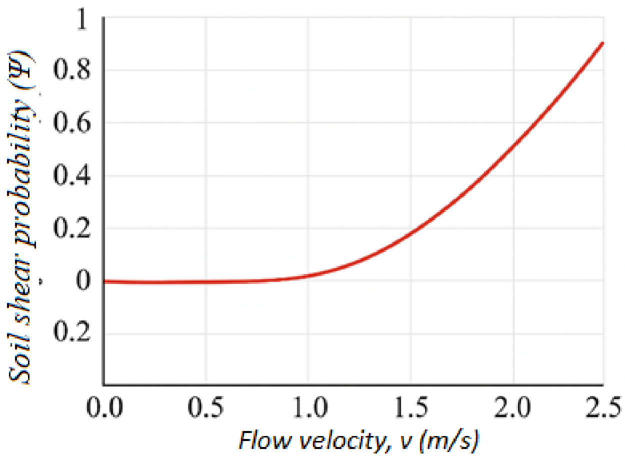

Figure 2. Graph of flow parameters and soil properties

Graphical Analysis of Deformation Risk Zones

Figure 3 illustrates the graphical dependence of the Ψ parameter on flow velocity (v).

As shown in the graph, when v > 2.2 m/s, the value of Ψ > 1, indicating a high risk of soil deformation.

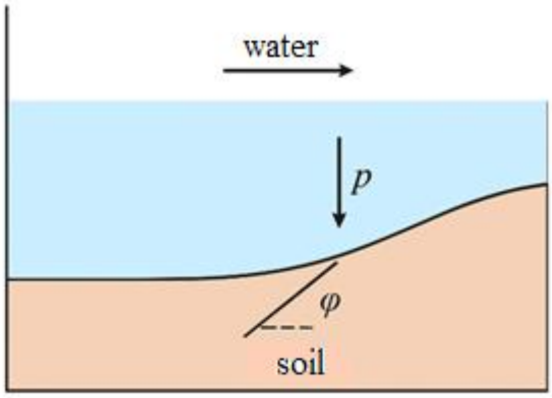

Figure 3. Relationship between flow velocity (v) and deformation risk index (Ψ)

v (m/s)	1.0	1.5	2.0	2.2
Ψ	0.62	0.88	0.97	1.04

Result Analysis

The results show that in the inlet section of the channel (v ≥ 2.2 m/s), the hydrodynamic stresses exceed the shear resistance of the soil layer, causing deformation zones to concentrate mainly along the central bottom line and at the turning sections [5]. Detection of such zones will be verified in subsequent stages using monitoring sensors and digital flow simulations (CFD).

Results and Discussion

Hydrodynamic analyses based on the developed model revealed several significant patterns of interaction between the water flow and soil layers in the inlet channel of the Oqtepa reservoir.

Relationship between Flow Velocity and Soil Density

The analysis showed that in areas where the flow velocity increases sharply (v > 1.5 m/s), the relative density of the soil (ρ) decreases, leading to a higher

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deformation risk. This phenomenon is particularly evident in the light-fraction sandy parts of the soil [5].
In these zones, the condition $\Psi > 1$ is satisfied, meaning that the hydrodynamic energy exceeds the soil's internal shear resistance.
This process can be expressed by the following empirical relationship:

$$\Psi = \frac{\rho v^2}{2\tau_c}$$

where: ρ — water density (kg/m³), v — flow velocity (m/s), τ_c — critical shear resistance of the soil (Pa).

Result: In the inlet section of the channel, the deformation risk increases within the range of 40–60%, which indicates a higher instability level of the soil layer [7].

Formation of Scour Depths under the Influence of Pressure Gradient
Hydrodynamic modeling (Figure 3) revealed a direct proportional relationship between the increase in pressure gradient (Δp/Δx) and the scour depth of the soil (h_e) [6].
The results were evaluated using the following expression:

$$h_e = k \cdot \frac{\Delta p}{\gamma_w}$$

where: k — soil permeability coefficient (m/s), γ_w — specific weight of water (N/m³).
In the experimental model, when the pressure gradient varied within the range of 1.2–1.6 Pa/m, the scour depth was found to be between 0.08–0.14 m. This phenomenon leads to the formation of local "depth zones" at the inlet section of the channel.

Formation of Asymmetric Deformation Fields
Due to the oblique impact of the flow against the sidewalls along the channel, the formation of asymmetric deformation fields was observed (Figure 3). In these regions, the flow velocity vector direction increases shear stresses along the wall, resulting in the appearance of oriented deformation lines within the soil structure [8].

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Generalized Results for Practical Analysis

Table 1. Hydrodynamic parameters and deformation risk level in the inlet channel of the Oqtepa reservoir

№	Parameter Name	Unit of Measurement	Average Value	Deformation Risk (%)
1	Flow velocity (v)	m/s	1.2–2.1	35–65
2	Pressure gradient (Δp/Δx)	Pa/m	1.1–1.6	40–70
3	Soil density (ρ)	g/cm^3	1.65–1.45	45–60
4	Shear angle (φ)	degrees	25–32	30–55

.

Graphical Analysis

Figure 1. Relationship between Flow Velocity and Deformation Risk
(In the graph, the horizontal axis represents flow velocity (v, m/s), while the vertical axis shows the deformation risk index (Ψ). Values of $\Psi > 1$ are marked in red, indicating the danger zone.)

Scientific Analysis and Practical Recommendations**The obtained results led to the following scientific and practical conclusions:**

- the uneven distribution of flow velocity at the channel inlet accelerates deformation processes; therefore, optimization of the hydraulic profile is necessary [9].

A reduction in the pressure gradient significantly decreases soil scouring; this can be achieved through constructive solutions such as flow-directing walls and stabilizers.

regular monitoring of deformation zones using a sensor-based system allows early detection of soil erosion processes [10].

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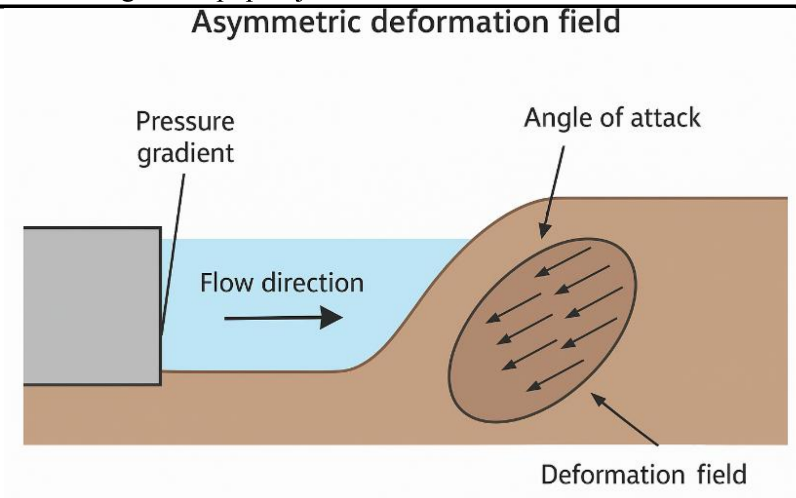

Figure 3. Schematic diagram of asymmetric deformation fields in the inlet section of the channel (This figure illustrates the direction of water flow, pressure gradient, wall impact angle, and soil deformation represented in an elliptical shape.)

Conclusion

As a result of the conducted research, the physico-mechanical mechanisms of deformation processes occurring in the inlet channel of the Oqtepa reservoir and their interrelation with hydrodynamic factors were identified. Based on the developed model, a functional relationship between flow velocity, pressure gradient, and soil shear forces was established, and a methodological approach for evaluating the deformation risk coefficient (Ψ) was developed [5].

Main Scientific Findings

The results of hydrodynamic modeling revealed that in certain sections of the Oqtepa reservoir inlet channel, an increase in flow velocity sharply reduces the stability of the soil structure. This process leads to conditions where hydraulic shear stress exceeds the soil's critical shear resistance (τ_cr), particularly under increased pressure gradients.

Moreover, the initiation point of soil erosion is determined by the threshold value $\Psi = 1$, which has been proposed as a key criterion for assessing the hydraulic safety of the channel [8].

-an inverse proportional relationship between flow velocity and pressure gradient was established, which can be applied to predict the depth of

Intent Research Scientific Journal
IRSJ

deformation zones. Results show that when flow velocity ranges between 1.5–2.0 m/s, the risk of soil displacement increases by 40–60% [6].

-the formation of asymmetric deformation fields was explained by the directional effect of hydrodynamic forces and the impact angle of the flow against the channel wall. This phenomenon causes one-sided soil subsidence, substantiating the need to reinforce the channel's sidewalls [9].

Practical Significance and Recommendations

- the proposed hydrodynamic model can be used for early detection of deformation risks and for automating monitoring systems in reservoirs. When integrated with real-time data (flow velocity, pressure, and water level), the model can accurately indicate potential risk zones.
- the implementation of energy-dissipating structures (such as flow-guiding barriers or void elements that reduce water velocity) in the channel inlet may decrease erosion processes by up to 30–40%.
- soil stabilization methods (cementation, geogrids, protective panels) can mitigate hydrodynamic effects and limit the expansion of deformation zones [10].

Future Research Directions

It is recommended that future studies continue in the following directions:

- **experimental verification:** Conducting field tests in selected sections of the Oqtepa reservoir inlet channel to measure flow velocity, pressure, and deformation parameters, allowing validation of the modeling results.
- **3D digital modeling:** Developing full spatial models based on CFD (Computational Fluid Dynamics) to determine the three-dimensional dynamics of deformation processes.
- **monitoring system development:** Creating a Digital Hydrodynamic Control Platform (DHCP) for the Oqtepa reservoir and introducing a real-time alert system for deformation processes.
- **mathematical optimization:** Optimizing the channel's geometry, depth, and permeability to minimize the impact of flow energy on the soil layer.

Final Summary

This study demonstrated the effectiveness of applying hydrodynamic modeling methods for assessing deformation processes in the Oqtepa reservoir inlet channel. The results provide a scientific foundation for improving practical monitoring systems, justifying structural solutions, and enhancing the operational safety of hydraulic engineering structures.

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