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Application of Bentonite as an Anti-Filtration Material in Hydraulic Engineering: A Case Study of the Tudakul Reservoir

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Abstract: Filtration through reservoir dam is a vital issue affecting the sustainability of hydraulic structures and the efficiency of water distribution. This study offers a comprehensive analysis of filtration management methods, focusing on bentonite as a filtration control membrane. The results of the Tudakul reservoir dam study highlight the structural challenges of filtration through porous soils, with water losses posing a huge threat to sustainability. Laboratory and theoretical studies monitor the performance of bentonite, which, due to its special swelling properties, creates a dense gel barrier when in contact with water. This study compares bentonite with alternative solutions, including concrete liners, comparing key parameters such as cost, ease of installation, self-healing properties and environmental impact. The results indicate that bentonite is a cost-effective, sustainable and durable filtration control membrane with large capacity for programs in water-scarce regions.

Keywords: Filtration, bentonite, hydraulic systems, Tudakul Reservoir, anti-filtration materials, water retention, filtration modeling, dam stability, sustainable materials.

1. Introduction

Filtration processes in hydraulic systems consisting of unlined canals and reservoirs are one of the key issues affecting the sustainability of these systems and the efficiency of water supply. Unlined canals and reservoirs are subject to water loss due to filtration through porous soils, which can lead to a decrease in water levels and even damage to the structure. Research in the field of filtration covers a wide range of problems: from theoretical models and laboratory experiments to practical answers to the issue of reducing water loss. This literature review examines the main theoretical and reasonable methods aimed at studying filtration procedures and methods for preventing water leakage.

Theoretical modeling of filtration is based at the legal guidelines of hydrodynamics and filtration principle. The fundamental principle of filtration changed into evolved within the works of Darcy, who proposed an equation describing the drift of liquid via a porous medium (Darcy, 1856). Darcy's components became the idea for modeling filtration techniques in hydraulic systems, taking into consideration such parameters as soil permeability, strain drop, and filtration price. Subsequently, the improvement of filtration principle continued in the works of Bauer and Kondakov, who investigated the impact of soil heterogeneity and their structural residences on filtration traits (Bauer & Kondakov, 1974).

To obtain a more accurate understanding of the filtration process in natural soils, the finite element method is used to take into account the complex shapes and structures of canals and reservoirs, as well as gradients in water saturation and changes in soil permeability with depth. Modern theoretical approaches to filtration modeling include the use of numerical methods and computer modeling to create complex multi-layer soil models, which is especially important for the analysis of unlined canals and reservoirs, where the soil structure is irregular and heterogeneous (Lapidus, 1989).

Practical studies of filtration processes have been conducted using laboratory experiments, field studies, and filtration monitoring at existing sites. One common method of laboratory research is scale modeling, where the soil and conditions of a reservoir or canal are reproduced in a controlled environment. Laboratory experiments make it possible to determine filtration coefficients for different soil types and to develop recommendations for the use of filtration control materials such as bentonite, geomembranes, and composite linings (Ignatenko, 1992). Field studies in unlined canals and reservoirs are conducted to assess actual filtration levels and to identify areas of increased water loss. Lapidus and Ignatenko propose methods for conducting such measurements, which include monitoring water levels, flow velocities, and water chemistry (Lapidus & Ignatenko, 1993). Particular attention is paid to the influence of external factors such as climate conditions and seismic activity, which can change the soil structure and increase filtration losses (Trukhachev, 1998).

Research shows that various anti-filtration materials and technologies are used to reduce filtration losses in unlined canals and reservoirs. Among the most effective methods are the use of bentonite coatings, geosynthetic membranes and injection solutions. Bentonite has a high degree of water-holding capacity and is able to form a waterproof barrier when in contact with water, which reduces water filtration through the pores of the soil (Yakhshiyev, 2023). Trukhachev and Fomin's works consider the use of geosynthetic materials such as geomembranes and geotextile coatings, which not only create a waterproof barrier, but are also resistant to mechanical damage. Experimental data show that geomembranes can reduce filtration losses by 80-90%, which is especially important for regions with a shortage of water resources (Fomin, 2001).

The study of filtration processes in unlined canals and reservoirs shows that filtration is a complex and multifactorial process, depending on the properties of the soil, the geometry of the structure and external conditions. Modern modeling methods and new materials for anti-filtration protection, such as bentonite and geosynthetic membranes, can significantly reduce water losses and improve the stability of reservoirs.

2. Materials and Methods

2.1. Study area description

The main parameters of the reservoir.

The Tudakul Reserve is a reserve situated 18 kilometers north-east of Kogon Railway State.The Kyziltepa district of the Navoi region is home to the dam gate of Tudakul reserve. It is situated 35 kilometers from the city of Bukhára and 10 kilometers from the Kyziltepa Railway Station. Using finances from regional water management organizations based on the materials of the Bukhara Regional Irrigation Systems Department project group, the Tudakul reservoir was constructed between 1965 and 1968. By blocking the path of the Tudakul depression, the dam was created. The dam's body is irregulatory. Indiscriminate pour of various soils (gravel, gypsum-mixed sand, and sand regardless of whether it is heavy or light) produces it. Investigations conducted in 1983 and 1993 concluded that the dam was unreliable. In order to receive the big water of 1998, on the basis of the project, the dam level was raised to 228.00 marks. (Sh. Yaxshiyev, 2023)

Water is taken from the Zarafshan river by a 21.77-kilometer canal, and the second turn of the Đmu-Bukhara canal through a 5-kilometer canal and the Khar Khur hydraulic dam fill the water reservoir.When there is excess water in the Zarafshan River following the irrigation season, water is taken from the river. According to Gapparov et al. (2023), the first chamber has a capacity of 100 m3/s, while the second has a capacity of 140 m3/s.

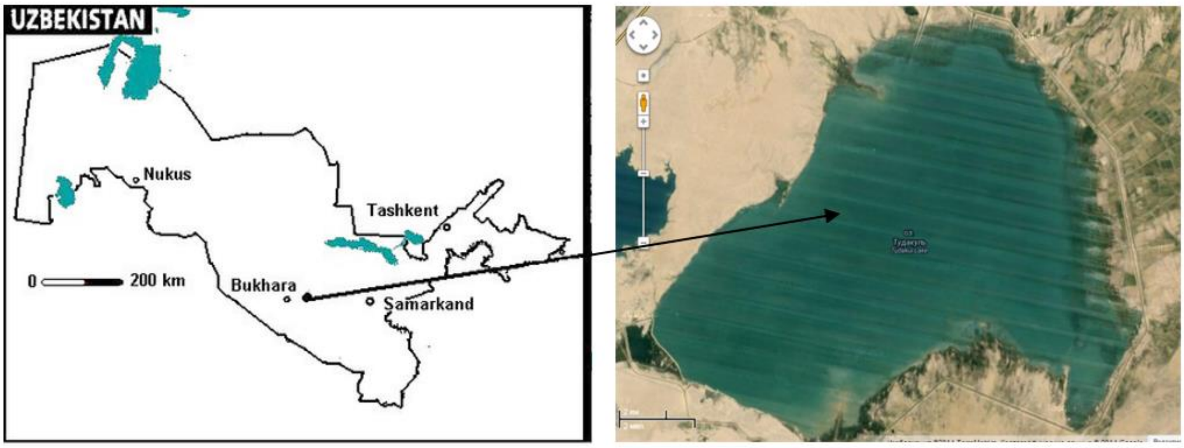


Figure 1. Tudakul reservoir.

2.2. Data collection

Climate: The region where the Akdaryo reservoir is located has hot summers and warm winters, with an average annual temperature of +14.1oC. The absolute maximum air temperature in the summer season is +46oC, the average in July is +26.9oC, and the absolute minimum air temperature in the winter is -32oC. Average annual precipitation is 144.2 mm. Precipitation is observed mainly in November-April. The period of most precipitation falls on December-March. Average annual evaporation is 1400 mm. (Gapparov, et.al., 2019)

Table 1. Chemical analysis of the soil in the dam

Location of analysis	HCO_3, %	Cl, %	SO_4, %	Ca, %	Mg, %	Na+K, %	Condensed residue	pH
Todakol reservoir	0,03	1,290	1,991	0,245	0,027	1,48	5,19	5,5

2.3. Methodology. Understanding the pattern of movement of the filter water along the reservoir's body and its impact on its constituent parts is essential to evaluating the aggressiveness of the filter flow in the reservoir's body. In order to guarantee the stability of the dam and its parts, the assessment's findings are crucial.

In a turbulent flow, or without pressure, filtration water typically passes through the body of the reservoir dam. It is known that the filter flow has an open surface and travels from the upper part of the dam to the lower part when there is no pressure. The pressure differential in this instance is composed of DH = H1-H2 (Ganjegunte & Flynn, 2017).

The filter flow gradient is typically represented by (J) and is the ratio of the filter flow pressure difference (DH = H1-H2) to the length of the filter path in the dam body:

$$J = \frac{\Delta H}{l} \quad (1)$$

The filtration flow in the dam body obeys Darcys law. Such movement can be observed in detail in the soil of the dam body and foundation, including sand, sand and sandy rocks.

The consumption of filtration flow in the dam body is expressed as follows based on the law created by the French scientist Darcy:

$$Q = K_f F \frac{\Delta H}{l} = K_f F J \quad (2)$$

Here: Q – filtration flow consumption, i.e. the amount of water filtered through the soil per unit of time, m^3/sut;

K_f- filtration coefficient, the amount representing the ability of the soil to pass water through the dam itself, m/sut;

F – filtration flow zone cross-sectional surface, m^2;

l- the length of the filtration flow path, m;

ΔH- the difference of pressures in the upper and lower befs, m;

We divide both sides of the equation by (F) to express the filtration rate,

$v = K_f J$

Therefore, according to Darcys law, the rate of filtration or movement of the flow in the soil forming the dam body (n) is directly proportional to the filtration pressure gradient (J) and the filtration coefficient.

Pressure gradient $J = \frac{\Delta H}{l} = 1$ in the circumstances $v = K_f J$ equation $v = K_f$ takes the form, that is, the filtration coefficient is numerically equal to the filtration rate.

The following conditions must be met when evaluating the filtration strength of the soil dam and its anti-filtration elements. (Ruziev, Samiev, Mustafoyeva, Nortaev, & Yakhshiev, 2023)

$J_{est,m} = \frac{\Delta H}{t_2} \leq J_{cr,m} = J_{dop}$ yoki $J_{est,m} \leq \frac{1}{\gamma_n} J_{cr}$ (3)

Here: $J_{est,m}$- average gradient in the calculated element of the dam.

γ_n - reliability coefficient of the dam (I- class -1,25; II- class -1,2; III- class -1,15; IV- class -1,1);

J_{cr} - permissible average filtration gradient of an earthen dam.

Bentonite can be used as a method to combat filtration.

Bentonite is a natural clay mineral with unique swelling properties when in contact with water. In particular, sodium bentonite, which has a high water-holding capacity, is able to increase in volume and form a dense gel layer that prevents water penetration. These properties make bentonite an excellent material for creating waterproof barriers in water bodies and reservoirs (Singh, & Reddy, 2013).

3. Results.

Measuring works of hydraulic elements of the channel in natural field studies were carried out using the Doppler device of the brand "River Surveyor S5 System Manual". This modern scientific measuring device is equipped with an acoustic measuring device Sontek S5 ADP M9 and software Sontek RiverSurveyor Live for controlling the device, collecting and analyzing data, allows for fast and reliable provision of measurement data (Fig. 2.).

Fig. 2. Doppler device River Surveyor S5

From the water balance equation, the losses in water flow lost between the sections are determined as follows:

$$\Delta Q = Q_f + Q_b + Q_T \, , \qquad (4)$$

here: Q_f - amount of water lost through filtration, [m^3/s], Q_b - the amount of water lost by evaporation, [m^3/s], Q_T - technical losses [m^3/s].

Using the given expression (4), the filtration flow rate is determined as follows:

$$Q_f = Q_A - Q_B \pm Q_q - Q_b - Q_T \qquad (5)$$

The filtration coefficient is determined based on the amount of filtration from the dam body.

The findings of the analysis show that the changes in cross-sectional patterns of filter flow ingredients were influenced by the irregulatory construction of the Tudakul Reservoir dam utilizing various soils. Factors such as fluctuating material permeability and aggressive chemical components in the water were shown to be responsible for the changes in the ingredients (Zhang & Li, 2011).

The dam of the Tudakul reservoir is made of cored local soil. The calculation of the average gradient of filtration pressure for such dams is calculated by the following formula for the core and prism.

For the kernel $J_{dop} = \frac{1}{\gamma_n} J_{cr}$

For the prism $J_{dop} = \frac{1}{\gamma_n} J_{cr}$

According to the calculation results, the analysis reveals that, in the section between the first, second, and third meters, the leakage water movement speed, the pressure difference, and the filtering path are large, whereas, in the section between the third, fourth, and fifth meters, the opposite is true, or the filtering water movement speed, the pressure difference, and the filtering path is long. This leads to a sharp reduction in the pressure gradient in the section between the third, fourth, and fifth pezometers. Water stagnation is seen in the pressure gauges if the pressure gradient is extremely small.

Based on the findings of the conducted research, the effectiveness of soil filtration varies. This difference is dependent on the quantity of the gradients between the piezometers in the dam; if the gradient is at the standard level, the filter behavior changes in accordance with the law; if there is a quantity, the pressure gradient is too small; and the saturation of water is also measured in pezometers.

As part of the study, changes in the quality of water collected in the basin of the Tudakul reservoir and taken from the lower bef drainage were analyzed in order to identify the conditions that result from the aforementioned changes and to evaluate the impact of water filtering on the structural elements (Table 2 and Pic. 3).

Table 2. *Chemical analysis of water quality collected in Tudakul reservoir basin*.

	pH	Solid residue, mg/l	Amount of basic ions dissolved in water, mg/l					
			$HCCl_3$	*Cl*	*SO''_4*	*$Ca^{\cdot\cdot}$*	*$Mg^{\cdot\cdot}$*	$Na+ K^-$
Reservoir basin	7,4	265,7	140	266	770	180	79	239
Drainage water	7,59	842,8	268	275	782	125	85	254

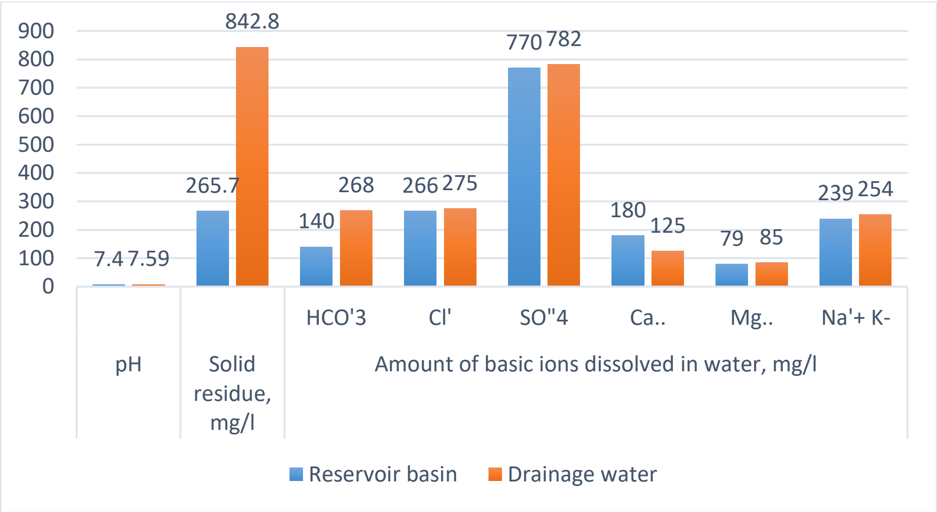
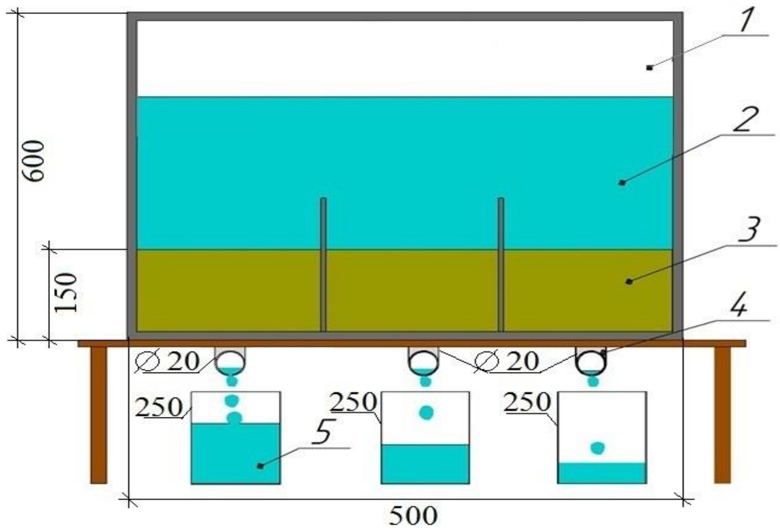


Figure 3. Diagram of chemical analysis of water quality collected in Tudakul reservoir basin.

To reduce the impact of filtration, a special device was proposed, which was tested in laboratory conditions using bentonite. The device has the shape of a parallelepiped, 50 cm long, 40 cm wide and 60 cm high. The side walls of the device are made of glass material. (Fig. 4). This, in turn, makes it possible to control the hydraulic processes inside the device. The device parameters were developed in accordance with regulatory documents. In laboratory studies, the filtration coefficients of bentonite clay, channel soil, a mixture of bentonite clay and channel soil were determined.

The device was used to conduct experiments on samples made from mixtures of bentonite clay and channel soil in percentage ratios (5%, 10%, 15%, 20%, 30%, 40%, 50%) and determine the filtration coefficients.

According to the results of the studies, the degree of water permeability of the lining (screen) reached the soil sample at 30-35% bentonite clay mixture.



1 - transparent container; 2 - water layer; 3 - bentonite soil layer; 4 - water outlet pipe; 5 - water tank.

Figure 4. Schematic diagram of the experimental device.

The data obtained in laboratory studies were analyzed using mathematical statistics methods (Fig. 5). Based on the analysis, the following relationship was obtained for determining the relative filtration coefficient of the lining (screen): $n_0 = 0,0552\left(\frac{p_g}{p_b}\right)^{0,554}$, (6)

here: $n_0 = \frac{k_e}{k_g}$ - relative screen filtration coefficient; p_g - amount of bed soil [%], p_b - amount of bentonite clay [%].

Based on the collected data obtained as a result of theoretical and laboratory studies, a calculation of the volume of bentonite and an assessment of the costs of its use as a blanket (anti-filtration screen) in front of the dam were developed, the main parameters were determined and a comparative analysis was carried out.

Initial data and assumptions

Dimensions of the dam: Let's assume that the dam is an area in front of the dam that is 200 meters long and the width of the dam. Let's take the width of 100 meters as an average value.

Bentonite layer thickness: Let the bentonite screen thickness be 0.3 meters (30 cm), which is the standard value for filtration protection.

Calculation of the volume of bentonite

We use the formula for volume by multiplying the area by the layer thickness.

The square of dejection

Area of the ponur = Length x Width = 200 m x 100 m = 20000 m^2

Volume of bentonite

Volume of bentonite = Area of the dam × Thickness of the bentonite layer = 20,000 m2 × 0.3 m = 6,000 m^3

Cost estimate

Let's assume that the cost of bentonite is 50 USD per cubic meter.

Total cost of bentonite = Volume of bentonite × Cost per m^3 *= 6,000* m^3 *× 50 USD/*m^3 *= 300,000 USD*

To estimate the cost of the concrete coating in front of the dam, we will use the following data and assumptions:

Size of coating: Let's assume that the concrete coating is needed on a section 200 meters long and 100 meters wide, similar to the bentonite dam.

Thickness of concrete coating: Usually, a concrete thickness of 0.3 meters (30 cm) is used for anti-filtration and protective coatings.

Cost of concrete: Let's take the cost of concrete, including placement, as 100 USD per cubic meter.

Coverage area = Length × Width = 200 m × 100 m = 20,000 m^2

Volume of concrete

Volume of concrete = Coverage area × Thickness of concrete layer = 20,000 m^2 *× 0.3 m = 6,000* m^3

2. Estimating the cost of concrete cover

Now let's calculate the total cost based on the cost of 100 USD per cubic meter.

Total cost of concrete = Volume of concrete × Cost per m3 = 6,000 m^3 *× 100 USD/*m^3 *= 600,000 USD*

The estimated cost of concrete cover for the area in front of the dam is 600,000 USD.

4. Discussion.

Benefits of using bentonite as a lining

- Cost-effective: Bentonite is relatively inexpensive and requires less installation costs than concrete lining. It provides reliable protection against filtration at a relatively low cost.
- Self-healing properties: Bentonite has the ability to self-heal (swell) when in contact with water, which helps to eliminate minor defects and cracks. This increases the durability and stability of the coating.
- Environmentally friendly and safe: Bentonite is a natural material, does not pollute water and is safe for the environment, unlike some synthetic materials.
- Flexible installation: The bentonite layer easily adapts to surface irregularities and does not require complex equipment for installation, which reduces labor costs and installation time.

Table 3. Comparison with other methods

Characteristic	Bentonite	Concrete
Cost	Low (300,000 USD for 200 x 100 m)	High
Ease of installation	High, minimal preparation required	Low, requires careful preparation
Self-healing properties	High	None
Environmental friendliness	High, natural material	Medium, concrete may have an impact
Resistance to damage	Tall, self-sealing	Medium, cracks may occur

Comparative analysis of the advantages of bentonite for anti-filtration before a dam compared to concrete coatings and geotextile membranes:

- Cost-effectiveness

- ✓ Bentonite: The cost of bentonite coating is lower, especially for large volumes. Bentonite is cheaper both in materials and in installation, which makes it cost-effective.
- ✓ Concrete: More expensive in materials and labor-intensive to install. Requires a prepared base and special conditions for installation, which increases costs.
- ➢ Ease and flexibility of installation
- ✓ Bentonite: Easy to install, can adapt to the relief and unevenness of the surface. Does not require complex equipment and high labor costs.
- ✓ Concrete: Requires careful surface preparation and compliance with the technology during installation, which increases the time and cost of installation.
- ➢ Resistance to damage and durability
- ✓ Bentonite: Highly resistant to small soil movements and minor deformations. Forms a dense barrier that can adapt to operating conditions.
- ✓ Concrete: High strength, but sensitive to mechanical and thermal deformations. May crack when the ground moves, which requires repair.
- ➢ Environmentally friendly
- ✓ Bentonite: Natural material, safe for the ecosystem. The use of bentonite minimizes the impact on the environment.
- ✓ Concrete: The environmental impact may be higher due to the use of chemical additives. Concrete production is associated with carbon dioxide emissions, which can have a negative impact on the environment.

Concrete pavement will cost approximately 600,000 USD, which is almost twice the cost of bentonite blanket (300,000 USD). Concrete has high strength and durability, but requires significant costs for materials and installation, which makes it a less economical solution for this task.

5. Conclusion.

In conclusion, filtration in hydraulic systems, particularly through unlined canals and reservoirs, represents a significant challenge to the sustainability of these systems and the efficiency of water supply. Unlined structures lose water due to filtration through porous soils, potentially causing structural damage and impacting water levels. Theoretical and practical research into filtration processes provides insight into reducing these losses, from Darcy's foundational models of water flow through porous media to modern laboratory and field studies aimed at assessing soil permeability, filtration rates, and effective anti-filtration materials.

One key solution is the application of anti-filtration materials like bentonite and geomembranes, which create waterproof barriers within the soil. Bentonite, a natural, cost-effective material, has demonstrated substantial effectiveness in controlling filtration due to its high water-holding capacity and self-healing properties when exposed to water. When used as an anti-filtration layer in unlined reservoirs, it not only reduces water losses but also adapts to the natural irregularities in soil structure, ensuring long-term durability and minimal environmental impact.

Comparative analyses indicate that bentonite offers cost-efficiency, ease of installation, and environmental sustainability superior to alternatives like concrete linings. Concrete, though strong and durable, requires more extensive preparation, higher installation costs, and lacks the flexibility and self-sealing properties of bentonite, making it a less economical solution. Ultimately, bentonite presents a viable option for improving the stability and efficiency of hydraulic systems, especially in regions facing water scarcity and high maintenance costs for traditional infrastructure solutions.

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