The improvement of safety and reliability of Ground dams and small pond dams

E V Vasilieva¹, V M Fedorov²

¹Department of Ecology and Industrial Safety, South Russian state Polytechnic University (NPI) named after M. I. Platov, 132, Prosveshcheniya St., Novocherkassk 346428, Russia.
²Department of Technosphere safety and environmental management Novocherkassk engineering and melioration Institute named after A. K. Kortunov Donskoy GAU, 111, st. Pushkinskaya, Novocherkassk 346428, Russia.

E-mail: karalenka5@yandex.ru

Abstract. Earth dams and dikes belong to the increased technology-related risk facilities, most of the accidents on which occur due to the facility design and construction errors. 60% of the more than three hundred dam and dike collapse accidents in various countries of the world over the past 100 years have been caused by filtration through the structure’s body, suffusion and loosening of the soil, and consequently, the crest and slope failure. This paper considers the issues of developing and creating more effective structural measures to combat the earth dam and dike defects and damages, based on well-known and proven design solutions considering the technical and financial capabilities of local repair and construction companies and economies, as well as their mechanical equipment and local raw materials available.

1. Introduction
The current technical conditions of reservoir-forming dams and dikes on many ponds and industrial waste storage facilities in the Russian Federation should be considered unsatisfactory to a large extent, which poses a real technogenic threat to economic facilities, settlements, the population, and the environment.

However, most of the defects, deformations, and damages at such facilities could be avoided if highly effective and reliable means were used to protect the earth dams or dikes from filtration through their body and base [1-4]. Such waterproofing means include impervious cores, screens, and diaphragm walls. It should be emphasized that impervious cores and screens reduce the piezoelectric gradients of the filtration flow, lower the depression curve level, and increase the operational reliability of the downstream slope and the water-tightness and the reliability of the entire dike (dam). Thereby, the water barriers minimize defects and destructive processes occurring in the structure’s body – the soil suffusion, heaving, and freezing, the emergence of cracks, holes, passages, and voids, and the erosion and collapse of slopes [4-7]. If the impervious screens are water-tight elements more repairable and convenient for the performance of work, then the arrangement of the core requires less material, the core is more easily integrated with the concrete part of the dam and is less sensitive to the dam base and body settlement. Like screens, cores are made of cohesive (low-permeable) soils arranged layer-by-layer in parallel to the dam base (Figure 1). However, due to the compacted soil
layers arranged in parallel to the retaining structure base, the impervious cores that are, figuratively speaking, the walls on the way of filtration flows often do not ensure the required reduction in the lower dam (dike) zone depression curve level and the filtration flow rate, and an acceptable height of the filtration flow exit to the downstream slope.

**Figure 1.** Diagram of a Dam with a Core of Horizontal Soil Layers: a) – initial; b) – reduced.

2. **Main part**
Let us further consider a new design solution [2], which recommends arranging the compacted core soil layers not horizontally but obliquely to the downstream pool at an angle to the surface of the water-retaining structure base (Figure 2), while the numerical angle value depends on the safe values of the filtration flow parameters. When the layers are obliquely arranged (patent No. 127763), their overlying (more compact) zones are involved in the work to a greater extent and more effectively counteract the filtration flow.

**Figure 2.** Diagram of a Dam with a Core of Inclined Soil Layers a) - the dam cross section; b), c) – cores of inclined soil layers; 1 - dam; 2 - core; 3 - inclined core layer; 4 – downstream pool; 5 – upstream pool; 6 - the dam base; 7 - depression curve.
Let us prove the practical feasibility of arranging the soil core layers obliquely to the downstream pool at an angle to the dam base on specific examples below [2-10].

Given:
- \( H_1 = 12.5 \, \text{m}; \quad d_0 = 2.5 \, \text{m}; \quad H_{\text{dam}} = 15 \, \text{m}; \quad b_{\text{dam}} = 8.0 \, \text{m}; \quad m_1 = 3.0; \quad m_2 = 2.0; \)
- the dam body permeability coefficient \( K_{\text{body}} = 1.5 \, \text{m/day}; \) the core soil filtration coefficient \( K_{\text{core}} = 0.05 \, \text{m/day}; \)
- top core thickness \( \delta_1 = 1.6 \, \text{m}; \)
- bottom core thickness \( \delta_b = 4.0 \, \text{m}; \)
- reduced core thickness \( \delta_{\text{red}} = \delta_{av}\left(\frac{K_{\text{body}}}{K_{\text{core}}}\right) = 2.8\left(\frac{1.5}{0.05}\right) = 84 \, \text{m}; \)
- reduced dam crest width \( \delta_{\text{red}} = \delta_{dam} + \delta_{av}\left(\frac{K_{\text{body}}}{K_{\text{core}} - 1}\right) = 8 + 2.8\left(\frac{1.5}{0.05 - 1}\right) = 89.2 \, \text{m}. \)

Permeability of water through the dam with the core is calculated by the formulas:

\[
\frac{q_T}{K_{\text{body}}} = \frac{H_{\text{dam}} - d_0 - h}{m_1} \cdot 2.3lq \cdot \frac{H_{\text{dam}}}{H_{\text{dam}} - h}; \tag{1}
\]

\[
\frac{q_T}{K_{\text{body}}} = \frac{h^2 - h_1^2}{2S_{\text{red}}}; \tag{2}
\]

\[
\frac{q_T}{K_{\text{body}}} = \frac{h_1}{m_2}; \tag{3}
\]

\[
S_{\text{red}} = b_{\text{red}} + m_2(H_{\text{dam}} - h_1); \tag{4}
\]

where \( h \) is the filtration flow depth in a separate section; \( h_1 \) is the finite ordinate value (at the point of exit to the downstream slope) of the depression curve or the seepage height; \( q_T \) is the specific filtration flow rate, and \( S_{\text{red}} \) is the reduced distance from the coordinate origin to the downstream slope.

The identity of the left parts of formulas (2) and (3) means the equality of the right ones:

\[
\frac{h^2 - h_1^2}{2S_{\text{red}}} = \frac{h_1}{m_2}; \tag{5}
\]

Equality takes place at \( h = 11.4 \, \text{m} \) and \( h_1 = 1.1 \, \text{m}: \)

\[
b_{\text{red}} = 8.0 + 2.8\left(\frac{1.5}{0.05 - 1}\right) = 89.2 \, \text{m};
\]

\[
S_{\text{red}} = 89.2 + 2[15 - 1.1] = 117.0 \, \text{m};
\]

\[
(11.4^2 - 1.1^2) / 2 \cdot 117.0 = 1.1 / 2.0 = 0.55 = 0.55.
\]

Let us find the value of the specific filtration flow rate:

\[
q_T = K_{\text{body}} \cdot \frac{h^2 - h_1^2}{2 \cdot S_{\text{red}}} = 1.5 \cdot \frac{11.4^2 - 1.1^2}{2 \cdot 117.0} = 0.825 \, \text{m}^3/\text{day}.
\]
Thus, the specific filtration flow rate $q_f$ through the structure body is higher than the permissible value $q_{f(perm)}$ and should be reduced to increase the safety and reliability of the earth dam. It can be reduced (see formula 3) by decreasing the seepage height $h_1$ and thereby, the depression curve level in the lower dam zone, which is ensured by arranging the core soil layers (hereinafter referred to as the ‘core layers’) with a slope.

On the examples below, we show how $h_1$ and $q_f$ decrease when the compacted core layers are arranged with a slope:

Example No. 1. At the core soil layer inclination angle $\alpha=10$ degrees.

When arranging the core soil layers in parallel ($\alpha=0^\circ$) to the base surface, the core soil permeability coefficient $K_{core} = 0.05$ m/day. When arranging them with a slope, this coefficient is calculated by the formula:

$$K_{core} = K_{core} \cdot \beta \text{ m/day},$$

where $\beta$ is the coefficient determined by the below equation considering the different compaction of the upper and lower (bottom) zones of the core soil layers:

$$\beta^2 = \frac{1 + \tan^2 \alpha}{1 + (\varepsilon \cdot \tan^2 \alpha)},$$

where $\alpha$ is the angle at which the core soil layers are inclined to the dam base; $\varepsilon$ is the ratio of the permeability coefficients of the underlying (less compact) and overlying zones of the core soil layers. Depending on the soil type, the soil layer thickness, and the number of the compaction machine (e.g., roller) passes over the same trace, $\varepsilon = 5 \div 20$. We adopt $\varepsilon = 10$.

Let us calculate

$$\beta^2 = \frac{1 + 10^2}{1 + (10 \cdot 10^2)} = \frac{1.031}{1 + 3.109} = 0.251,$$

$$\beta = 0.50.$$

When arranging the compacted soil layers with a slope, the soil core permeability coefficient will be:

$$K_{core} = K_{core} \cdot \beta = 0.05 \cdot 0.5 = 0.025 \text{ m/day},$$

At $h = 11.835$ m and $h_1 = 0.692$ m, the right parts of equations (2) and (3) will be:

$$b_{red} = 8.0 + 2.8 \left(1.5 / 0.025 - 1\right) = 173.2 \text{ m};$$

$$S_{red} = 173.2 + 2 \left(15 - 0.692\right) = 201.82 \text{ m};$$

$$\frac{11.835^2 - 0.692^2}{2 \cdot 201.82} = \frac{0.692}{2} = 0.346;$$

Let us find the specific filtration flow rate:

$$q_f = 1.5 \cdot \left(11.835^2 - 0.692^2\right) / (2 \cdot 201.82) = 0.519 \text{ m}^3/\text{day}$$
The found value of the specific filtration flow rate is less than the permissible one, thus, the values $h_1 = 0.692$ m and $q_r = 0.519$ m$^3$/day are within the range of permissible values contributing to the safe and reliable dam operation.

On example No. 2, we will show that at $\alpha = 20^\circ$, the dam safety and reliability are further improved.

Example No. 2. At the core soil layer inclination angle $\alpha = 20$ degrees, we find

$$\beta^2 = \frac{1 + \tan^2 20^\circ}{1 + (10 \cdot \tan 20^\circ)^2} = \frac{1 + 0.3639^2}{1 + 13.247} = 0.0795,$$

$$\beta = 0.28.$$

When arranging the compacted soil layers with a slope ($\alpha = 20^\circ$), the soil core permeability coefficient will be:

$$K_{\text{core}} = K_{\text{core}} \cdot \beta = 0.05 \cdot 0.28 = 0.014 \text{ m/day},$$

At $h = 12.102$ m and $h_1 = 0.438$ m, the right parts of equations (2) and (3) will be:

$$b_{\text{red}} = 8.0 + 2.8(1.5 / 0.014 - 1) = 305.2;$$

$$S_{\text{red}} = 305.2 + 2(15 - 0.438) = 334.3;$$

$$\frac{12.102^2 - 0.438^2}{2 \cdot 334.3} = 0.438$$

$$\frac{2 \cdot 334.3}{2.0} = 0.219 = 0.219.$$

The specific filtration flow rate:

$$q_r = 1.5 \cdot \frac{12.102^2 - 0.438^2}{2 \cdot 334.3} = 0.328 \text{ m}^3/\text{day}$$

$$q_r = 0.328 \text{ m}^3/\text{day} < q_{r(\text{perm})} = 0.65 \text{ m}^3/\text{day}$$

Consequently, at $\alpha = 20^\circ$, the depression curve in the lower part of the dam decreases more significantly (the seepage height $h_1 = 0.438$ m), and the filtration flow rate is much lower.

3. Conclusion

Thus, arranging the impervious core of low-permeable compacted soil layers with a slope (at an angle to the base $\alpha = 10-20^\circ$) will reduce the filtration flow rate by 1.5-2.5 times and significantly decrease (more than 2.0 times) the height of the filtration flow seepage to the downstream slope as compared to the core of horizontally arranged soil layers, which provides a high water-tightness and stability of the dam (dike) bodies, prevents the soil suffusion, heaving, and freezing, as well as collapse and settlement, and therefore, reduces the risk of emergency and ensures the safety of nearby economic, cultural, and historical objects, and the population living in the surrounding areas.

Reference

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