

EXPERIMENTAL INVESTIGATION OF SEEPAGE PATTERNS AND STRUCTURAL DEFORMATION IN EARTH-FILL DAMS

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Abstract:

This paper presents a laboratory assessment of seepage behavior in the earth dam of the Qamashi Reservoir. A 1:100 physical model was used to examine water movement through a compacted loam dam body and to identify the development of the phreatic surface. The experimental results were also compared with field observations obtained at section PC16+30. The model was installed in a transparent hydraulic flume, while the upstream water level was kept constant at a value corresponding to elevation 487.68 m in the prototype. Changes in the wetting zone and the phreatic surface were monitored at five-minute intervals. Water temperature was 19.2 °C and water density was 999.6 kg/m³; the bulk density of the model soil was 1650 kg/m³. Seepage water appeared at the downstream side after approximately 41 hours. The model crest experienced 2 mm of vertical settlement, while the mean hydraulic gradient was 0.12. No visible soil washing, suffusion, or sudden deformation occurred during the test. The laboratory phreatic profile generally followed the trend observed in the field, although a noticeable difference occurred near the downstream toe because the model did not include the prototype drainage system. The results indicate that physical modeling can provide useful qualitative information about seepage development in an earth dam, provided that model simplifications and scale limitations are considered when interpreting the results.

Keywords: earth dam; seepage; physical model; Qamashi Reservoir; phreatic surface; hydraulic gradient; loam soil; field monitoring.

Introduction

Earth dams are widely used in water-resources and hydraulic engineering because they can be constructed from locally available soils and can provide effective storage and regulation of water. Their long-term performance depends not only on the strength and deformation characteristics of the embankment but also on the way water passes through the dam body and its foundation. Seepage is

therefore one of the principal processes that must be considered when evaluating the condition and operational safety of an earth dam [1].

Seepage develops because of the difference in hydraulic head between the upstream and downstream sides of the structure. As water moves through interconnected soil pores, the saturated zone inside the embankment changes and a free phreatic surface is established. Its position influences the degree of saturation, pore-water pressure, seepage discharge and the hydraulic condition of the downstream slope. A rise of the phreatic surface can increase the saturated portion of the embankment and may alter slope stability. For this reason, monitoring and interpretation of the phreatic surface are important components of dam assessment [2].

Unfavorable seepage conditions may be associated with internal erosion, suffusion, migration of fine particles, excessive pore pressure, wetting of the downstream slope and local deformation. These processes do not necessarily appear simultaneously, which makes direct observation and repeated monitoring valuable. In practice, seepage is investigated by analytical calculations, numerical simulations, laboratory experiments and field measurements. Each approach provides different information and has its own limitations [3].

Analytical methods are useful for understanding the general principles governing seepage, but they may simplify soil heterogeneity, compaction conditions and actual boundary conditions. Numerical methods can represent complex geometries and material properties in greater detail, but their results require appropriate input data and should ideally be checked against experimental or field observations. Physical models provide another way to observe the development of a seepage field under controlled conditions [4].

Previous research has shown that soil hydraulic conductivity has a direct influence on seepage discharge, phreatic-surface position and hydraulic gradients. The response of an earth dam also depends on reservoir-level changes. When the reservoir rises, the saturated zone generally expands, while a falling water level may be followed by a delayed adjustment of the internal seepage field. Temperature is another parameter that should be controlled during laboratory studies because it affects the viscosity of water and, consequently, hydraulic conductivity [5].

Studies of operating earth dams in Uzbekistan emphasize the importance of regular observation of piezometric levels, seepage discharge, drainage performance and deformation. For the Qamashi Reservoir, such observations are particularly relevant because the dam has been in operation and its seepage behavior must be considered under actual field conditions. At the same time, laboratory information that directly compares a physical loam-soil model with field observations remains useful for understanding the main pattern of seepage development [6].

The objective of this study was to investigate seepage development in a 1:100 physical model based on the geometry of the Qamashi Reservoir earth dam, determine the position and general shape of the phreatic surface, record model crest settlement and hydraulic gradient, and compare the laboratory pattern with observations from section PC16+30 [7].

Materials and Methods

The Qamashi Reservoir earth dam was selected as the study object. The investigation concentrated on the internal seepage path, development of the phreatic surface, hydraulic gradient and deformation associated with water movement through the embankment. Winter field observations from section PC16+30 were used as a reference for comparison. This section is operationally important because a water outlet structure is located in the same area.

The experiment was conducted using a transparent hydraulic flume. The flume was approximately 3.5 m long, 1.0 m wide and 0.5 m high, allowing the wetting process to be observed directly through its side walls. A perforated distribution wall was installed upstream to make water delivery more uniform. Openings on the downstream side allowed seepage water to leave the experimental zone rather than accumulate inside the flume.

The model embankment was constructed from loam soil and placed in successive layers. Each layer was compacted evenly in order to obtain a relatively uniform soil body and reduce the possibility of artificial

preferential flow paths. The prototype dam has a height of about 15 m and a crest width of approximately 7 m. A geometric scale of 1:100 was adopted for the laboratory model. The model dimensions were therefore reduced in accordance with the selected linear scale.

Several elements of the prototype were deliberately omitted because the principal purpose of the test was to observe seepage through a comparatively homogeneous loam body. In particular, the downstream drainage system, the concrete lining on the upstream slope and the water outlet structure were not reproduced. These simplifications are important when the experimental results are compared with the actual dam.

The model soil was characterized by laboratory testing. Its bulk density was determined from mass and volume and was 1650 kg/m³. Grain-size characteristics were assessed using laboratory methods consistent with GOST 12536–2014. Water used in the test had a measured density of 999.6 kg/m³ and a temperature of 19.2 °C. The temperature was recorded as a control parameter rather than as an independent variable in the experiment.

A 1 × 1 cm coordinate grid was marked on the transparent wall of the flume before the test. This reference system was used to record the water level, wetting front, phreatic-surface points and changes in the model profile. Water was introduced gradually from the upstream side until the model water level corresponded to the prototype elevation of 487.68 m.

Observations were made every five minutes. The movement of the wetting front and the gradual formation of the phreatic surface were recorded until seepage reached the downstream side and the internal water profile became comparatively stable. At the end of the test, the elevation of the crest was compared with its initial position to estimate vertical settlement.

For comparison with field conditions, laboratory coordinates of the phreatic surface were converted according to the adopted scale. The main comparison criteria were the general shape of the phreatic surface, piezometric-head distribution and the behavior of the seepage field near the downstream toe. The mean hydraulic gradient was evaluated from the difference in hydraulic head between the upstream and downstream water levels divided by the estimated seepage-path length.

Results and Discussion

The experiment showed a gradual development of seepage through the loam embankment. The upstream water level remained constant during the test, which provided a stable boundary condition for observing the internal response of the model. The recorded water temperature was 19.2 °C, the water density was 999.6 kg/m³ and the soil bulk density was 1650 kg/m³ [8].

Seepage water reached the downstream side approximately 41 hours after the beginning of the experiment. This relatively gradual development demonstrates that water required a considerable period to pass through the compacted soil body under the adopted laboratory conditions [9]. During the observation period, no visible washing of soil particles, suffusion, or localized boiling was detected. The absence of these effects is consistent with the generally gradual nature of the observed seepage process [10].

The phreatic surface developed progressively as the wetting zone moved from the upstream side toward the downstream side. Its overall shape was smooth, with a continuous decline in hydraulic head along the direction of seepage [11]. When the laboratory profile was compared with field observations from PC16+30, the two profiles showed a generally similar trend. This agreement suggests that the physical model was capable of reproducing the principal qualitative pattern of seepage in the selected section [12].

A difference became more pronounced near the downstream toe. The laboratory profile showed a steeper decline at the final observation point than the field profile. The most direct explanation within the study is the absence of the prototype drainage system in the model. Drainage affects the downstream seepage boundary and therefore influences the final position of the phreatic surface. Consequently, the difference does not necessarily indicate a contradiction between the model and field behavior; rather, it illustrates the influence of structural elements that were intentionally simplified [13].

A vertical settlement of 2 mm was measured at the model crest after the experiment. No abrupt displacement of the slopes or visible distortion of the model geometry was observed. The settlement value should be interpreted only as a response of the laboratory model under the adopted loading, compaction and seepage conditions. Because of scale effects and differences between the model and the prototype, the measured 2 mm cannot be directly treated as the settlement of the actual dam [14].

The calculated mean hydraulic gradient was 0.12. Under the conditions adopted for the experiment, this value remained below the specified limiting range used for the assessment. This result indicates that the average seepage gradient did not approach the critical condition during the test. Nevertheless, a mean value represents the overall seepage field and may conceal locally higher gradients. Localized assessment is therefore required if the objective is to identify zones with a greater potential for seepage-related problems [15].

The results also demonstrate why physical-model findings should be interpreted together with field measurements. The laboratory test was performed with one reservoir level and one controlled temperature. In an operating reservoir, water levels vary over time and the internal seepage field responds to those changes. The prototype also contains drainage and other structural components that influence seepage. Thus, the laboratory model is best considered a tool for understanding the general development of seepage rather than a complete reproduction of every operational condition.

Overall, the close qualitative agreement between the laboratory and field phreatic profiles supports the usefulness of the selected modeling approach. The experiment provided direct information about the timing of seepage appearance, development of the wetting zone, phreatic-surface shape, model settlement and mean hydraulic gradient. These observations can complement numerical calculations and field monitoring when assessing the seepage condition of an earth dam.

Conclusion

A 1:100 physical model was used to investigate seepage behavior in the earth dam of the Qamashi Reservoir. The experiment demonstrated a gradual movement of water through the compacted loam body, with seepage reaching the downstream side after about 41 hours. No visible soil washing, suffusion or sudden deformation was observed.

The phreatic surface developed in the laboratory had a general configuration similar to that recorded during field observations at section PC16+30. The model crest settled by 2 mm, while no abrupt slope displacement was detected. The mean hydraulic gradient was 0.12 and remained within the adopted limits under the experimental conditions.

The study confirms that a physical model can be used to obtain qualitative information about seepage development and phreatic-surface behavior in an earth dam. At the same time, the results are subject to the limitations of the experimental setup. The absence of the drainage system, concrete lining and water outlet structure, together with the use of a single water level and temperature, affects the direct transfer of the results to the prototype.

Further investigations should include tests at several reservoir levels and temperatures, a more detailed determination of local hydraulic gradients, and comparison with numerical seepage calculations. Expanded field monitoring would also improve the basis for evaluating the relationship between model behavior and the actual operating condition of the dam.

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