Experimental and Seepage Analysis of Gabion Retaining Wall Structure for Preventing Overtopping in Reservoir Dams

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Abstract: Recently, heavy rains caused by climate change have resulted in dam failures due to overtopping. This study presents a design method aiming to prevent overtopping failures by applying gabion retaining walls at the dam crest. Simulations, experiments, and measurements were conducted to evaluate the effectiveness of this design. The design framework aims to establish a system in which gabion retaining walls prevent overtopping when water levels exceed the crest of the dam, efficiently draining seepage water into the dam body through vertical filters. Research findings indicate that implementing dam crest core and geomembrane design effectively prevents seepage and saturation of the downstream slope during overtopping events. Notably, the reservoir dam operates in a stable manner, as seepage water passing through the dam body is directed solely to the toe drain. Overall, this design approach suggests its potential as a practical solution by significantly reducing hazards resulting from heavy rainfall.

Keywords: aging; dam crest core; overtopping prevention structure; reservoir dam; seepage control; water level

1. Introduction

Over 70% of dams worldwide are constructed using soil; consequently, they are vulnerable to leakage and internal erosion due to heavy rain and other factors [1,2]. Climate variability has exacerbated these vulnerabilities, increasing the frequency of dam failures [3]. The aging of dams is affected by various factors, such as structural conditions, soil properties, infiltration control, and drainage performance, causing dams to degrade over time, thereby limiting their ability to withstand heavy rainfall [4–7].

In South Korea, most agricultural reservoirs are earth-filled dams, referred to hereinafter as earthen dams. Of the 17,080 reservoirs, 99% are earthen dams, with 87% constructed over 50 years ago [8]. The historical context, including the agricultural infrastructure focus of the Japanese colonial period and the Korean War, promoted the economical and rapid construction of earthen dams [9]. Most of these dams were constructed to low design standards in the 1900s, without considering their service life [10]. In 2020, 22 reservoirs failed during the rainy season, and the primary failure factor was age. Although existing evidence is insufficient to conclusively attribute failures to dam aging, there are perspectives suggesting that the challenges in explaining the phenomenon as solely due to rainfall may be linked to older dams constructed in an era without modern designs or mechanical equipment. These older dams were more prone to exhibiting inhomogeneous zones. When water levels in a dam increase owing to rainfall, seepage water accumulates in the path of least resistance in the uneven fill zone, indicating potential susceptibility to failure under such conditions [11–13]. From 2010 to 2020, failures in 104 reservoirs in
Korea occurred most frequently during the monsoon period between July and October and were mainly attributed to aging and heavy rainfall. Failures at 11 locations (10.5%) of water leaks and piping were attributed to dam aging, whereas those at 90 locations (86.5%) were associated with spillway-boundary failure, overtopping, and slope failure [8].

Global statistics on earthen dam failures have identified the primary causes of failure as overtopping (35.9%) and piping (30.5%) [1,14]. However, in Korea, reservoir dam failures caused by heavy rainfall were dominant in 2010 [8]. Figure 1 illustrates the number of dam failures according to dam type and failure cause. The failure rate was not significantly influenced by the type of dam, such as zone, core, and homogeneous dams (See Figure 1). Zoned-type dams, generally considered the most stable, exhibited the highest failure rate (53%). These findings suggest that design approaches focusing on controlling seepage within the dam body may be insufficient regardless of the dam type. The results highlight the vulnerability of all earthen dams to slope erosion and overtopping during intense rainfall, thereby posing a potential failure risk. The failure of an earthen dam owing to overtopping is a multifaceted process influenced by several factors, including dam compaction, material, crest width, and slope. Several studies have highlighted this complexity, suggesting that more dam failures are due to overtopping than to internal erosion [15–18].

![Figure 1](image_url)

**Figure 1.** Number of dam failures according to dam type and failure cause.

To mitigate the risks associated with overtopping, several different slope protection methods have been used on downstream slopes, including ripraps, gabions, vegetative cover, roller-compacted concrete, and biopolymers [19–21]. In some cases, the dam crest is constructed with a parapet and a flat concrete foundation for support [10,22].

However, these methods cannot guarantee the continued safety of dams in small earth reservoirs with frequent water level fluctuations, as there is a high possibility of differential settlement between the dam body and its foundation. Since dam crest railing installations and slope protection methods do not fundamentally prevent overtopping, there is a need for a more comprehensive solution from a methodological perspective [23,24]. An alternative approach involves safeguarding the dam body by installing flood protection structures at a particular water level [25–27]. While gabion retaining walls are generally utilized to enhance slope stability and alleviate filter clogging at the slope end [28,29], integrating the design method with overtopping blocking functionality and a drainage system can also be effectively applied to dam crests. Specifically, the dam crest core, responsible for directing seepage water into the dam body during overtopping, collaboratively functions with the gabion, serving as its protective element. Additionally, seepage water induced into the dam is efficiently drained into the toe drain through a vertical filter. This integrated design underscores the critical importance of sustaining dam stability over prolonged overtopping periods, achieved through the harmonious interplay between each structural element.

Thus, in this study, a novel approach is proposed to prevent overtopping by installing a gabion retaining wall structure at the dam crest. This approach is designed to alleviate water pressure within the dam body through the structure's own weight and the drainage function of the vertical filter, even in cases where water levels exceed the dam crest. In particular, the proposed approach applies to small-sized reservoirs because of the smaller scale of potential disasters in emergencies coupled with a higher probability of overtopping damage.
Therefore, the installation of a dam crest overtopping prevention structure using a gabion retaining wall was simulated. The simulations were based on finite element-based leakage analysis and large-scale, indoor, model experiments. The behavioral characteristics of overtopping prevention structures were analyzed in response to changes in water levels, the stability of the results was verified, and practical applications in the field were explored.

The remainder of this manuscript is structured as follows. Section 2 describes the materials and methods followed in the study, including the selection of target reservoir and soil samples, design conditions, measurements, and finite element analysis. Section 3 presents the results, and Section 4 summarizes the findings of the study.

2. Materials and Methods

2.1. Target Reservoir and Soil Samples

Zoned earthen dams are commonly found in Korea. In this study, we evaluated the effectiveness of a zoned earthen dam for preventing reservoir failure due to overtopping and enhancing the stability of aged dams. Gyeryong Reservoir is an old reservoir, constructed in 1964, with a height of 15.2 m and located in Gyeryong City, Republic of Korea. This dam satisfies the objectives of this study. Soil samples (core and embankment) were collected from the borrow pit used to construct the reservoir, and experimental values were obtained through indoor experiments (see Figure 2). The particle size distribution curves and physical properties of the soil samples used in the model construction are listed in Table 1.

![Soil particle distribution.](image)

**Figure 2.** Soil particle distribution.

**Table 1.** Geotechnical properties of the tested materials.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$G_s$</th>
<th>$k_v$ (m/s)</th>
<th>$W_{opt}$ (%)</th>
<th>$d_{max}$ (kN/m³)</th>
<th>$c$ (kPa)</th>
<th>$\phi$ (°)</th>
<th>USCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill zone</td>
<td>2.65</td>
<td>$3.22 \times 10^{-6}$</td>
<td>14.0</td>
<td>17.3</td>
<td>16.7</td>
<td>24.0</td>
<td>SC</td>
</tr>
<tr>
<td>Core</td>
<td>2.69</td>
<td>$3.11 \times 10^{-3}$</td>
<td>23.0</td>
<td>15.8</td>
<td>34.3</td>
<td>9.0</td>
<td>CL</td>
</tr>
<tr>
<td>Filter</td>
<td>2.62</td>
<td>$7.82 \times 10^{-5}$</td>
<td>-</td>
<td>19.6</td>
<td>-</td>
<td>40.0</td>
<td>SP</td>
</tr>
<tr>
<td>Crushed stone</td>
<td>2.65</td>
<td>$2.55 \times 10^{-4}$</td>
<td>-</td>
<td>22.8</td>
<td>-</td>
<td>-</td>
<td>SP</td>
</tr>
</tbody>
</table>

$G_s =$ specific gravity; $k_v =$ vertical coefficient of permeability; $d_{max} =$ maximum dry density; $c =$ cohesion; $\phi =$ internal friction angle; USCS = unified soil classification system; SC = clayey sand; CL = clay with low plasticity; SP = poorly graded sand.

2.2. Design Conditions for Overtopping Prevention Structures

For overtopping prevention structures, the design conditions must address the complex displacement behavior and potential defects arising from the differential settlements caused by adding superstructures to dams. For concrete structures in particular, exceeding
the design storage capacity of the dam can result in water leakage and overtopping failure, thus emphasizing the critical nature of displacement behavior analyses [30].

Considering that constituent materials and water levels affect vulnerable areas when the overtopping water level is reached, this study proposes a design of an overtopping prevention structure wherein a core is installed at the center of the dam crest to prevent water leakage-induced cracks (see Figure 3).

![Figure 3. Overtopping prevention structure.](image)

2.3. Model Dam Configuration and Measurement Location

The experimental soil tank model, constructed from concrete, steel, transparent, and reinforcing materials, measured 95 cm (height) × 270 cm (length) × 670 cm (width). The experimental dam model was constructed to a scale of 1/30 of the standard cross-section of a prototype reservoir (see Figure 4). Based on the actual reservoir cross-section, model slopes of 1:2.0 (downstream) and 1:2.5 (upstream) were applied. The vertical filter in the filter zone extended to the bottom of the gabion structure, and a horizontal filter was installed in the toe drain. Homogeneity of the fill layers was ensured by compacting 10 cm thick layers using soils passing a 4.75 mm sieve. The relative compaction for each layer exceeded 90% maximum dry density. Pore water pressure (PWP) gauges with rated capacities of 50 kPa were used to measure water leakage at several locations: below the upstream bottom (P1, depth of 25 cm), at the bottom of the dam center (P2, depth of 20 cm), above the downstream bottom (P3, depth of 5 cm), below the dam crest core (P4, depth of 44 cm), and at the top of the downstream slope (P5, depth of 38 cm). Linear variable differential transformers with rated capacities of 50 mm were used as vertical and horizontal displacement meters centered on the dam crest core of the upstream (H1, V1) and downstream (H2 and V2) slopes. All measured values were recorded on a computer via a data logger.

The overtopping prevention structure comprised gabions, geomembranes, and a central core (see Figure 3). This core was installed between the upstream and downstream gabion retaining walls using formwork (see Figure 5) to address potential events related to rising water levels. The gabions, placed on both the upstream and downstream sides of the dam crest, had a height of 12 cm, width in the range of 4–6 cm, and length of 210 cm; the reduction ratios considered were based on gabion retaining wall standards [31]. The stepped gabion retaining wall was installed according to the design standards, ensuring that the front of the upper gabion step had a minimum width half that of the lower gabion step. Crushed stone samples filtered using 5 mm and 10 mm sieves were used as fill material [31]. A geomembrane was installed between the core and gabion. The core, geomembrane, and gabion were connected by wires to prevent gaps owing to conflicting material properties and to ensure close adhesion between the materials.
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Figure 4. Experimental model and measurement installation location.

Figure 5. Construction process. (a) formwork, (b) installation of core and gabion retaining walls, (c) settlement gauge installation, and (d) reservoir completion.

2.4. Finite Element Analysis

Dam seepage behavior is affected by several factors, including compaction, drainage methods, physical properties of the structure and soil, saturation, and water level. To achieve an approximate solution to this complex physical phenomenon, the conditions of the experimental model must be replicated. The analysis was performed using GTS NX software (v2.1) and the finite element method. A two-dimensional stress–seepage coupled analysis was performed because no protruding parts or specific designs existed within
the dam body. This approach considered both water flow owing to porosity and ground deformation owing to loading. The Van Genuchten model was applied to represent the unsaturated characteristic function, and the parameters were selected based on the soil properties used in the model experiment [32,33]. Tables 2 and 3 list the soil properties and water level conditions used in the experiment and analysis, respectively.

**Table 2.** Parameters of the soil–water characteristic curve used in the analysis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(\theta_s)</th>
<th>(\theta_r)</th>
<th>(\alpha)</th>
<th>(n)</th>
<th>(m(1−1/n))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill zone</td>
<td>0.46</td>
<td>0.034</td>
<td>1.60</td>
<td>1.37</td>
<td>0.270</td>
</tr>
<tr>
<td>Core</td>
<td>0.38</td>
<td>0.007</td>
<td>0.80</td>
<td>1.09</td>
<td>0.083</td>
</tr>
<tr>
<td>Filter</td>
<td>0.43</td>
<td>0.045</td>
<td>14.50</td>
<td>2.68</td>
<td>0.627</td>
</tr>
</tbody>
</table>

\(\theta_s\) = residual water content; \(\theta_r\) = saturated water content; \(a, n, m\) = curve fitting parameters.

**Table 3.** Water level conditions.

<table>
<thead>
<tr>
<th>Water Level</th>
<th>Prototype Water Level (m)</th>
<th>Model Water Level (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood water level (S1: FWL)</td>
<td>14.6</td>
<td>44.0</td>
</tr>
<tr>
<td>Dam crest water level (S2: DWL)</td>
<td>15.2</td>
<td>51.0</td>
</tr>
<tr>
<td>Overtopping water level (S3: OWL)</td>
<td>16.2</td>
<td>54.0</td>
</tr>
</tbody>
</table>

The water level varies over time, ranging from the surface of the lower part of the upstream slope to the top of the gabion wall (h = 54 cm). This boundary configuration results in the water level fluctuating from the base of the dam, passing through the flood level and dam crest level, and eventually transitioning to an overtopping water level that exceeds the dam crest level. The outlet for draining seepage water was positioned at the end of the slope, where the toe drain was located (see Figure 6). In the analysis, the time boundary was set to match the conditions applied in the experiment, causing an increase in the flood level (S1: 44 cm), dam crest level (S2: 51 cm), and overtopping water level (S3: 54 cm) every 24 h. Toe drains and gabions were defined as the drainage conditions. Gravity was applied to identify the dam body displacement with respect to the water level.

**Figure 6.** Boundary conditions of the analysis.

The model constraint was as follows: the bottom of the analysis model was set as a fixed boundary to ensure all deformations occurred exclusively within the dam body. The mesh shape was automatically generated based on a 2 cm square grid because the material near the dam crest core and the vertical filter could complicate the mesh composition.

3. Results and Discussion

Experimental models provide insights by simulating diverse conditions; however, the real-time monitoring of internal dam conditions is challenging, as it is dependent on measurements. Although real-time measurements can reveal physical changes in seepage and deformation, reliability may be compromised if seepage or leakage occurs at
3. Results and Discussion

Experimental models provide insights by simulating diverse conditions; however, real-time measurement analysis should be combined with model observational results for improving reliability. Numerical analysis offers visual information on structural changes to aid the comprehension of the phenomenon. However, this approach is limited because it cannot reflect dynamic environmental changes. Therefore, to leverage the strengths of each method and to enhance reliability, the review of the infiltration and displacement behavior during water level changes was conducted through numerical analysis, model observation, and real-time measurements in parallel.

3.1. Seepage Characteristics and Displacement Distribution Analysis

Figure 7 illustrates the seepage lines for each of the three (overtopping, dam crest, and flood) main water level distributions in the dam. On reaching the flood level (S1, t = 30 min), a seepage line was formed from the center of the dam, extending through the lower part to the slope end, indicating that seepage had not occurred. At the flood level (S1, t = 24 h), the upstream fill zone exhibited a certain degree of saturation; at this point, the seepage line drained to the slope end through a point slightly lower than the center of the vertical filter. At the same flood level (S1, t = 24 h), dam crest water level (S2), and overtopping water level (S3), the seepage line descended linearly toward the center of the vertical filter, highlighting the significant effect of the filter on the reduction of the seepage line. This result indicates that a difference as small as 24.5 times in the permeability coefficient between the vertical filter and fill zone can significantly impact the drainage efficiency. Figure 8 shows the PWP distribution. When the flood water level (S1) was continuously maintained, the water pressure affected the gabion structure area. The ranges of the PWP at the dam crest water level (S2) and overtopping water level (S3) exceeded 74% of those in the gabion structure area. However, the PWP changes in the dam body and downstream slope are insignificant. These results suggest that the drainage system incorporated with the vertical filter designed beneath the gabion retaining wall operated effectively. Additionally, the dam crest core suppresses infiltration, thereby limiting the water pressure expansion in the gabion structure and downstream slope.

![Seepage lines at overtopping, dam crest, and flood water levels.](image)

Figure 7 illustrates the changes in the horizontal (x-axis) and vertical (z-axis) displacements. The displacement values are extremely low because only stress changes due to water pressure were considered in the analysis, unlike experiments that reflect continuous phenomena, such as material inhomogeneity and scour progress. As the reliability of the quantitative values could not be determined, this analysis focused on qualitatively analyzing the overall displacement trend.

At the flood level (S1), the initial displacement began at the top of the upstream side of the gabion. At the dam crest water level (S2), the displacement area expanded from the top of the upstream-side gabion to the bottom of the downstream-side gabion, indicating that saturation progressed in the downstream fill zone. At the overtopping water level (S3), the displacement further increased, showing a pattern of gradual settlement toward the downstream side. These results indicated that the upstream recharge zone was already...
saturated, and no further deformation occurred, whereas the gabion sunk downstream as saturation progressed in the downstream recharge zone.

![Figure 7](image_url)

**Figure 7.** Seepage lines at overtopping, dam crest, and flood water levels. (a) (b)

Overall, gabion walls, dam crest cores, and vertical and horizontal filters are considered effective design methods for preventing the upper saturation of the downstream slope by reducing seepage lines.

### 3.2. Observation of Dam Deformation

When installing the gabion retaining wall structure on the dam crest, the interface between the existing dam and the overtopping prevention structure becomes hydraulically vulnerable; therefore, the seepage behavior at the interface should be assessed. Accordingly, piping and deformation behaviors were monitored depending on each water level stage to evaluate the effectiveness of installing overtopping prevention structures for improving the stability of reservoir dams.

Figure 10 illustrates the results of observing the deformation in the gabion structure and downstream slope at different stages: initial flood level (S1: 44 cm), flood level (S1: 44 cm), dam crest water level (S2: 51 cm), and overtopping water level (S3: 54 cm). As shown in Figure 10a, during the initial flood level (S1: 44 cm), there was no deformation singularity. However, over time, as shown in Figure 10b, some gaps appeared at the boundary between the gabion, the contact surface of the upper part of the dam crest, and, owing to drying shrinkage, the core. Because the effects of drying shrinkage increase when the core is exposed to the atmosphere for an extended period, the interconnection of the upstream and downstream gabions might require using strip material containing concrete or asphalt at the boundary between the core and gabions.

![Figure 8](image_url)

**Figure 8.** PWP distribution at different water levels. (a) S1: height, 44 cm (t = 30 min); (b) S1: height, 44 cm (t = 24 h); (c) S2: height, 51 cm; and (d) S3: height, 54 cm.

![Figure 9](image_url)

**Figure 9.** Total displacements of stepped gabion retaining wall. (a) S1: height, 44 cm (t = 30 min); (b) S1: height, 44 cm (t = 24 h); (c) S2: height, 51 cm; and (d) S3: height, 54 cm.
were observed throughout the overtopping water level, which suggests that the designed or asphalt at the boundary between the core and gabions.

upstream and downstream gabions might require using strip material containing concrete spreading down the downstream slope. Figure 10d presents the results of the dam deformation and water leakage at the overtopping water level (S3: 54 cm). No changes were observed throughout the overtopping water level, which suggests that the designed system maintained a steady state. However, assessing the stable state requires verification through a comparison with the measured values inside the dam body when transitioning from the dam crest water level (S2) to the overtopping water level (S3).

Overall, a comprehensive examination of flood prevention structures across different water levels revealed that overtopping prevention structures prevent overtopping and effectively block water leakage from the downstream slope. Furthermore, no dam deformation or water leakage was observed near the overtopping prevention structure during the experiment. Water leakage occurred solely through the toe drain located at the end of the slope on the downstream side. These results are highly meaningful, suggesting that the horizontal filter and toe drain contribute to constraining the expansion of the saturation region. Although some aspects, such as drying shrinkage, require improvement, the findings indicate the potential practical application of the proposed method in preventing disasters associated with reservoir failure.

3.3. Measurement Results

Figure 11 shows the PWP and displacement measured in the overtopping prevention structure. In this experiment, after establishing the water level upstream of the reservoir dam, the supply of additional water for maintaining the water level was limited to identify changes in the displacement behavior of the overtopping prevention structure and the PWP inside the dam body. During the flood level (S1, 44 cm), the PWP on the upstream slope (P1) gradually decreased over time after the water level increased. This decrease was attributed to an upstream water level reduction caused by water infiltrating the dam body, indicating that the infiltration process proceeded smoothly. The slope reductions of PWP under flood (S1, 44 cm) and dam crest (S2, 51 cm) water level conditions were compared. Here, the slope of the PWP is associated with the operation of drainage structures such as filters or toe drains within the dam. The results show that the dam crest water level (S2) decreased the slope of the PWP by approximately 1.8 compared to that of the flood level condition (S1). These results suggest that seepage water is not adequately drained by the filter and toe drain, thereby posing a potential risk to dam stability owing to the seepage water retention.

During the period of the overtopping water level (S3: 54 cm), the decreasing trends of PWP at the upstream slope (P1) and the bottom of the dam center (P2) were greater than that at the dam crest water level (S2, 51 cm), indicating the effective operation of the filter and toe drain.

Figure 10. Deformation of the stepped gabion retaining wall. (a) initial state, (b) shrinkage phenomena, (c) blockage of seepage water, and (d) steady state.
water levels directly affected the displacement. In contrast, the downstream horizontal water pressure when the water level increased, and the seepage water drained through the vertical filter, may be necessary to reduce the likelihood of forming a potential saturated zone below the dam crest core at the dam crest water level (S2, 51 cm), indicating the effective operation of the vertical filter and toe drain.

Figure 11. Measured values of the PWP and displacement.

Meanwhile, the PWP at the bottom of the dam center (P2) increased rapidly during the dam crest water level (S2, 51 cm). This rapid increase might be because the saturated area formed in the upstream fill zone extended to the bottom of the center of the dam. In this experiment, the upstream water level was reached in 1 h, and there was no gradual saturation process at the bottom of the dam.

The results suggest that dam body seepage indicates a potential saturation at the top rather than at the bottom during the rainy season as water flows into the reservoir and upstream water levels rise rapidly. Moreover, this result indicates that, in terms of sudden water pressure fluctuations, the dam crest water level (S2, 51 cm) may show greater instability than the flood (S1, 44 cm) and overtopping (S3: 54 cm) water levels. Conditions like those of the dam crest water level (S2) were maintained at the bottom of the downstream fill zone (P3), below the dam crest core (P4), and at the top of the downstream fill zone (P5). The PWP recorded below the dam crest core (P4) barely affected the seepage water pressure when the water level increased, and the seepage water drained through the vertical filter efficiently. In contrast, the top of the downstream fill zone (P5) exhibited the lowest PWP throughout the experiment, indicating that the dam crest core effectively blocked water leakage.

Consequently, optimizing the design parameters, including the slope, thickness, and permeability coefficient of the vertical filter, may be necessary to reduce the likelihood of forming a potential saturated zone below the dam crest core at the dam crest water level (S2). The observed stability in pore pressure changed at each water level, indicating a generally stable trend, highlighting its potential practical application as an alternative for preventing overtopping problems.

The upstream horizontal displacement (H1) gradually increased from the flood level (S1) to the overtopping water level (S3) and moved downstream. The maximum value of this displacement was measured to be approximately 4 mm, suggesting that the upstream water levels directly affected the displacement. In contrast, the downstream horizontal...
displacement (H2) presented a minimal displacement in the range of 0–1 mm from the flood level (S1) to the overtopping water level (S3). This small displacement indicates that it contributes to the suppression of damage or overtopping of the dam crest owing to the structural movement caused by the high weight of the gabion structure. The upstream vertical displacement (V1) showed a slight increase and repetition from the flood level (S1) to the overtopping water level (S3). However, its effect on the settlement was minimal. By contrast, the downstream vertical displacement (V2) continuously increased at each water level. When the upstream water level decreased, a large settlement was expected owing to the weight of the overtopping prevention structure. However, no significant settlement was observed. These results indicate that the pressure effect of the overtopping prevention structure contributes to suppressing the expansion or deformation of the dam body owing to changes in the water level.

The overtopping prevention structure exhibited downstream movement, attributed to the saturation of the upstream fill zone. These findings suggest that a differential settlement might emerge. However, the horizontal displacement was approximately 0.5%, and the vertical displacement was approximately 0.2%, indicating that the effect of the overtopping prevention structure on the dam stability was negligible. Implementing a reservoir with an overtopping prevention structure based on the design presented in this experiment or implementing a more robust design can serve as a basis for reducing the risk of reservoir failure owing to overtopping.

3.4. Summary of Results

This study discussed the effectiveness and risk factors of an overtopping prevention structure through comprehensive results from analyses, model experiment observations, and real-time measurements. Regarding the infiltration suppression, the overtopping prevention structure completely obstructed water leakage through the dam crest core at the overtopping water level (S3), effectively preventing erosion on the downstream slope surface caused by leaked water. The vertical filter designed to guide the water seepage into the dam body achieved appropriate structural performance. With increasing water levels, the vertical and horizontal filters contributed to maintaining dam stability, preventing further escalation of the seepage line and PWP within the dam. In terms of displacement suppression, the pressure effect of the overtopping prevention structure effectively mitigated the horizontal and vertical displacements, thereby minimizing the risk of damage or overtopping owing to structural movement. A potential risk factor arising from installing the overtopping prevention structure was the occurrence of gaps at the boundary between the gabion and the core, which was attributed to the drying shrinkage of the dam ridge core. The findings suggest the need for certain improvements, such as addressing the drying shrinkage in the core. Nevertheless, the structural design, as demonstrated through the analysis results, observations from model experiments, and concurrent measurements, was considered effective in maintaining the stability of the overtopping prevention structure.

In contrast, when anticipating an increase in water level due to heavy rainfall, it is crucial to consider the potential for water leakage at the boundary between the structure and the dam crest in terms of overtopping height and resistance. Previous research findings on the parapet model, specifically designed for preventing dam overtopping, indicate that the design is restricted to a range of 0.5–1 m owing to the risk of water leakage at the dam crest interface [10].

This research model, however, can accommodate designs up to 2 m in height, with the expectation that water leakage can be effectively blocked by the dam crest core. Nevertheless, the increase in structure height introduces the possibility of deformation during seismic events, thereby necessitating additional consideration for earthquakes in the future.

As instances of heavy rain and flooding become more prevalent owing to abnormal climate conditions, the findings of this study should be explored further. This study
presents an alternative approach to reduce the failure likelihood resulting from overtopping in reservoir dams.

4. Conclusions

This study addresses the critical issue of overtopping collapse in aging agricultural reservoirs by introducing an overtopping prevention structure utilizing gabion retaining walls on the dam crest. Through comprehensive simulation analysis, model experiments, and measurements, the following significant conclusions have been drawn:

1. The overtopping prevention structure effectively blocks water leakage during overtopping events and prevents erosion downstream. Efficient drainage through vertical filters maintains stability, with a decrease in pore water pressure inside the dam, even under constant overtopping. This underscores the practical effectiveness of the structural approach.

2. Horizontal and vertical displacements were minimal, within 0.5% and 0.2% of the dam height, respectively, even with decreasing water levels. This stability is attributed to the pressure effect from the structure’s self-weight, indicating a low risk of damage or overtopping during changes in water level.

3. The integration of the dam crest core, horizontal and vertical filters, and toe drain effectively prevents saturation within the dam body, highlighting their indispensable role in maintaining the overtopping prevention structure. Optimizing parameters such as filter slope, thickness, permeability coefficient, and toe drain scale can further enhance stability and minimize risks during emergency situations.

4. Minor drying-shrinkage-induced deformations occurred in the gap between the dam crest core and gabion structure, but their impact on stability is minimal. No significant deformation from water leakage was observed, ensuring overall structural stability.

The dam crest core, filters, and gabion structures can maintain stability during continuous overtopping. However, broader discussions are needed to establish this structure as a viable option for preventing overtopping during abnormal rainfall. Future research should focus on developing engineering standards, including analyzing parameters like flood potential and optimal design height. Additionally, a comprehensive seismic stability assessment is essential for integrating overtopping prevention measures into taller dam structures.

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