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INTEGRATED ASSESSMENT OF SEEPAGE AND INTERNAL EROSION RISK IN EARTH DAMS UNDER VARIABLE RESERVOIR LEVELS USING FIELD MONITORING AND NUMERICAL MODELLING

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Abstract

Seepage is an inherent process in earth dams, but concentrated leakage, excessive pore-water pressure, filter incompatibility, and high local hydraulic gradients may initiate internal erosion and progressively reduce embankment safety. Reliable assessment is complicated by spatial variability in soil properties, uncertain construction quality, reservoir-level fluctuations, drainage deterioration, and the limited ability of visual inspection to identify subsurface defects. This study proposes an integrated framework combining field monitoring, engineering inspection, geotechnical testing, saturated-unsaturated seepage analysis, and risk-based interpretation. The framework uses reservoir level, piezometric head, drain discharge, turbidity, deformation, hydraulic conductivity, grain-size distribution, filter compatibility, and drainage performance. Steady and transient numerical scenarios are considered for minimum, normal, and maximum reservoir levels, partial drain blockage, a localized high-permeability defect, and rapid drawdown. Model outputs include the phreatic surface, pore-water pressure, total and zonal seepage discharge, local hydraulic gradients, and concentrated-flow zones. A composite internal erosion risk index integrates hydraulic loading, material susceptibility, filter and drainage deficiency, observed anomalies, and failure consequences. A representative zoned earth-dam model demonstrates that total seepage alone is not a sufficient safety indicator: distributed flow through effective filters and drains may be acceptable, whereas a smaller concentrated flow through an unprotected exit can be critical. The proposed method supports decisions on enhanced monitoring, drainage rehabilitation, filter improvement, grouting, cutoff construction, reservoir restrictions, and urgent intervention.

Keywords: Earth dam; seepage monitoring; internal erosion; piping; pore-water pressure; hydraulic gradient; numerical modelling; filter compatibility; transient seepage; risk assessment.

Introduction

Earth dams are widely used for irrigation, water supply, flood control, and hydropower because they can be constructed from locally available materials and adapted to different foundation conditions. Their long-term safety, however, depends on the controlled movement of seepage through the embankment, foundation, abutments, filters, drains, and interfaces with concrete structures. Seepage is not inherently unsafe: a properly designed dam is expected to transmit a limited quantity of water through stable and filtered pathways. The condition becomes hazardous when hydraulic forces detach and transport soil particles, leakage concentrates along cracks or contacts, drains lose capacity, or eroded material reaches an inadequately protected exit. Internal erosion includes concentrated leak erosion, backward erosion piping, contact erosion, and suffusion; each mechanism requires an erodible material, sufficient hydraulic loading, a viable seepage path, and conditions that allow erosion to continue [1]. The difficulty is that internal erosion may develop before clear surface evidence appears. Muddy seepage, increasing drain flow, wet zones, sinkholes, cracking, and settlement are important warning signs, but some become visible only after significant progression. Conversely, stable total seepage can conceal a redistribution of flow toward a narrow defect, while declining drain discharge may result from clogging rather than improved watertightness. Therefore, reservoir level, piezometric head, seepage discharge, turbidity, temperature, and deformation should be interpreted as related time series rather than isolated measurements [2,3]. Numerical modelling complements monitoring by estimating hydraulic conditions between instruments and locating high gradients, elevated pore pressures, concentrated flow, and ineffective drainage. Its reliability depends on realistic geometry, boundary conditions, material parameters, and calibration against measured heads and discharges. Variable reservoir levels make the problem transient. During filling, the phreatic surface and pore-water pressures develop gradually; during rapid drawdown, external water pressure may decrease faster than pore pressures dissipate within low-permeability zones,

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reducing effective stress and potentially controlling upstream-slope stability [4,5]. Internal erosion risk also cannot be reduced to one exit-gradient calculation. Soil gradation, plasticity, stress state, erodibility, filter retention, drainage continuity, seepage-path geometry, and unprotected exits determine whether erosion initiates and progresses [1,6]. Recent studies show that electrical resistivity tomography and other geophysical techniques can help identify anomalous seepage or internal defects when combined with geological, geotechnical, and monitoring data [7,8]. Despite these advances, many dams are still evaluated through fragmented procedures in which visual inspection, instrumentation, laboratory testing, numerical analysis, and risk classification are performed separately. The present study develops a unified methodology that links these evidence sources and distinguishes normal seepage behaviour from conditions requiring enhanced surveillance, preventive rehabilitation, urgent stabilization, or emergency action. The objectives are to establish a structured monitoring database, calibrate steady and transient seepage models, identify concentrated-flow and high-gradient zones, evaluate filter and drain adequacy, and integrate the results into a transparent internal erosion risk index.

2. Materials and Methods

The study was structured around a representative zoned earth dam so that the procedure can later be recalibrated with site-specific geometry and monitoring records. The model includes a 30 m high embankment, an 8 m crest, an inclined clay core, compacted shells, transition filters, a horizontal drainage blanket, a downstream toe drain, and a stratified alluvial foundation above a low-permeability layer. These dimensions are illustrative rather than site-certified. The investigation begins with a unified database containing as-built drawings, geological sections, construction and repair records, reservoir-level history, piezometric measurements, drain discharge, turbidity, deformation observations, and reports of wet areas, muddy seepage, sinkholes, or settlement. Field inspection covers the crest, slopes, abutment contacts, downstream toe, drains, conduits, and interfaces with concrete structures. Laboratory work includes grain-size distribution, Atterberg limits, density, porosity, hydraulic conductivity, dispersivity, and filter compatibility. Where justified, pinhole or hole-erosion testing is used to evaluate the erosion resistance of fine-grained materials. Monitoring data are interpreted against reservoir elevation, rainfall, temperature,

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and operating changes. Persistent increases in normalized seepage, rising piezometric response at a stable reservoir level, increasing turbidity, transported fines, or new wet zones are treated as anomalies. The saturated seepage relationship is expressed by Darcy's law:

$$\mathbf{q} = -\mathbf{K}\nabla H \quad (1)$$

where q is the specific-discharge vector, K is the hydraulic-conductivity tensor, and H is total hydraulic head. Total head is defined by:

$$H = \frac{u_w}{\gamma_w} + z \quad (2)$$

where the symbols denote pore-water pressure, the unit weight of water, and elevation head, respectively.

$$\frac{\partial \theta}{\partial t} = \nabla \cdot [\mathbf{K}(\theta)\nabla H] \quad (3)$$

where theta is volumetric water content and K(theta) is the conductivity function. The finite-element domain is divided into core, shell, filter, drain, foundation, and potential defect zones, with mesh refinement near the core-filter contacts, downstream toe, conduits, and foundation interfaces. The upstream boundary follows the reservoir hydrograph; the downstream face is treated as a potential seepage face; drains are assigned atmospheric pressure; and the basal low-permeability layer is modelled as no-flow. The initial steady-state model is calibrated against piezometric heads and measured seepage using:

$$RMSE_h = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(H_{k,\mathrm{cal}} - H_{k,\mathrm{obs}})^2} \quad (4)$$

and:

$$E_Q = \frac{|Q_{\mathrm{cal}} - Q_{\mathrm{obs}}|}{Q_{\mathrm{obs}}} \times 100\% \quad (5)$$

where calculated and observed piezometric heads are compared at N monitoring points, and calculated and measured seepage discharges are used in the relative-error term.

$$i = \frac{\Delta H}{L} \quad (6)$$

and the theoretical critical gradient is estimated as:

$$i_{\mathrm{cr}} = \frac{\gamma'}{\gamma_w} = \frac{G_s - 1}{1 + e} \quad (7)$$

with the gradient safety indicator:

$$FS_i = \frac{i_{\mathrm{cr}}}{i_{\mathrm{exit}}} \quad (8)$$

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where the parameters represent soil specific gravity, void ratio, theoretical critical gradient, and calculated local exit gradient.

$$IERI = \omega_1 HLI + \omega_2 MSI + \omega_3 FDI - \quad (9)$$

The weights sum to 1.00 and may be derived using the analytical hierarchy process with a consistency ratio below 0.10. A preliminary weighting scheme assigns 0.20 to HLI, 0.20 to MSI, 0.25 to FDI, 0.20 to OAI, and 0.15 to CI. The proposed management bands are: IERI < 0.25, routine monitoring; 0.25-0.50, enhanced surveillance; 0.50-0.75, preventive rehabilitation; and IERI >= 0.75, urgent stabilization or emergency action. Sensitivity analysis varies hydraulic conductivity, anisotropy, defect dimensions, reservoir loading, drain effectiveness, core thickness, and foundation stratigraphy. If classification depends strongly on one uncertain parameter, targeted investigation is recommended before a costly intervention.

Table 1. Integrated indicators for seepage and internal erosion assessment

Assessment domain	Principal data and indicators	Analytical purpose	Warning evidence
Hydraulic loading	Reservoir elevation, duration of high water level, filling and drawdown rate, head difference	Defines seepage forces and transient pore-pressure response	Unusually high or rapidly changing hydraulic head
Material susceptibility	Gradation, plasticity, dispersivity, permeability, density and internal stability	Evaluates particle detachment and transport potential	Gap-graded, dispersive, poorly compacted or erodible material
Filters and drainage	Filter compatibility, drain discharge, drain condition, width and continuity	Determines whether erosion can continue or be arrested	Clogged drain, missing filter, segregation or unfiltered exit
Monitoring response	Piezometric head, seepage discharge, turbidity, temperature, deformation and visual evidence	Detects departure from baseline behaviour	Rising normalized seepage, muddy flow, sinkholes, wet zones or abnormal pore pressure
Numerical response	Phreatic surface, pore pressure, flow concentration, exit gradient and drain contribution	Locates critical zones between instruments	Concentrated flow, high local gradient or downstream saturation
Failure consequences	Reservoir volume, downstream exposure, infrastructure, irrigated land and redundancy	Defines significance and urgency of intervention	Potential breach, flooding, service interruption or major agricultural loss

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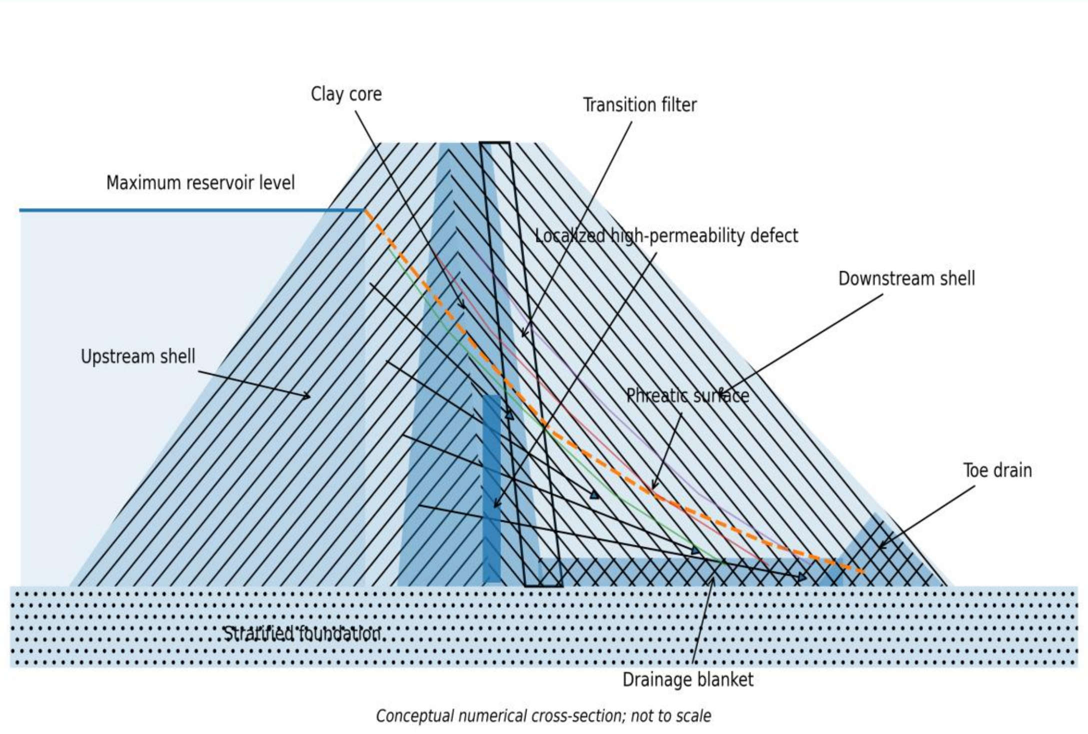

Figure 1. Conceptual seepage field in the representative zoned earth dam under maximum reservoir level

3. Results

The framework was demonstrated using the representative zoned earth-dam model under minimum, normal, and maximum reservoir levels, partial drain blockage, a localized high-permeability defect, and rapid drawdown. The values are illustrative numerical results and do not represent a certified diagnosis of a specific dam. Under normal retention, the calculated phreatic surface entered the horizontal drain without intersecting the downstream slope. Total seepage was 1.84 L/s, the toe drain collected approximately 78% of the flow, the downstream exit gradient was 0.31, and the gradient safety indicator was 3.29. At maximum reservoir level, seepage increased to 2.47 L/s, the foundation share of total flow rose from 21% to 29%, and the exit gradient increased to 0.43. The intact model therefore remained stable, but the higher head increased loading at the core-filter and foundation interfaces. Partial drain blockage produced a more adverse response even though measured drain discharge decreased to 1.63 L/s. The phreatic surface rose into the downstream shell, the maximum downstream piezometric head increased, the exit gradient reached 0.69, and the gradient safety indicator declined to 1.48. This result shows why declining drain discharge must

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not automatically be interpreted as improved watertightness: a simultaneous rise in piezometric head indicates restricted drainage and redistribution of flow. A localized defect with hydraulic conductivity two orders of magnitude higher than the intact core generated 4.16 L/s total seepage and a concentrated pathway near the core-foundation contact. The local exit gradient reached 1.17, exceeding the estimated critical gradient of the adjacent fine foundation material. The defect became especially critical where the protective filter was assumed to be locally thin or discontinuous. Risk classification reflected these mechanisms. The intact dam at normal level produced IERI = 0.24, corresponding to routine monitoring; maximum reservoir level increased the index to 0.38, requiring enhanced surveillance; partial drain blockage produced IERI = 0.61, indicating preventive rehabilitation; and the combined defect-filter deficiency scenario yielded IERI = 0.81, requiring urgent stabilization. The ranking was controlled more by concentrated hydraulic loading and defensive-system performance than by total seepage quantity. Rapid-drawdown analysis also showed that pore-pressure dissipation lagged behind the falling reservoir. At 1.00 m/day, pore pressure in the core remained about 37% higher than in the 0.25 m/day scenario at the same final water level, indicating a potentially critical condition for upstream-slope stability. Sensitivity analysis identified defect-zone conductivity, drain efficiency, and foundation anisotropy as the most influential parameters. Increasing intact-core permeability raised total discharge but did not create a critical gradient when filters and drains remained effective. By contrast, reducing drainage efficiency from 100% to 30% increased the maximum downstream piezometric head by approximately 46% and substantially expanded the saturated zone. The results support a monitoring system combining piezometers on both sides of the core, separate drain-flow measurements, turbidity and sediment observations, crest and slope deformation points, and targeted geophysical surveys where anomalous seepage cannot be localized. The preferred interventions are therefore drain rehabilitation, restoration of filter continuity, targeted grouting or cutoff treatment for concentrated foundation flow, and additional instrumentation rather than a general objective of reducing total seepage without identifying its pathway.

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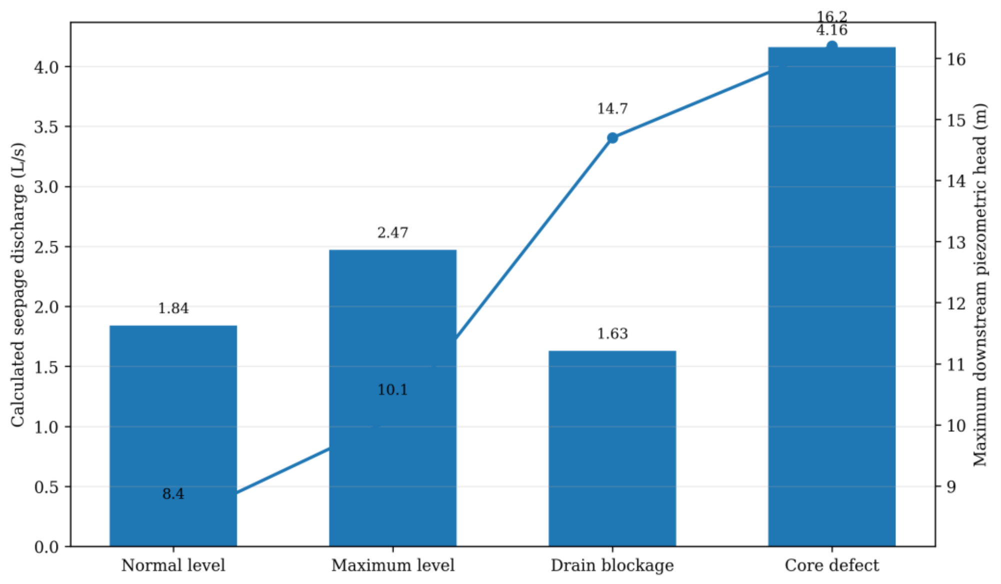

Figure 2. Calculated seepage discharge and maximum downstream piezometric head for the representative scenarios

4. Discussion

The representative analysis demonstrates that seepage safety in an earth dam is governed less by the absolute quantity of water passing through the structure than by the location, concentration, filtration, and detectability of the seepage path. The intact model transmitted 2.47 L/s at the maximum reservoir level without reaching a critical local gradient because the flow remained distributed and was intercepted by continuous filters and functioning drains. By contrast, the localized core defect produced a concentrated pathway near the core-foundation contact, where the calculated local gradient exceeded the theoretical critical value and the assumed reduction in filter thickness created a plausible continuation route for particle transport. This distinction is consistent with the staged internal erosion framework, in which hydraulic loading alone does not cause failure unless erosion initiates, an unfiltered or inadequately filtered exit permits continuation, the pathway progresses, and detection or intervention is unsuccessful [1]. Accordingly, a single allowable-seepage threshold is inadequate for dam-safety decisions. The same discharge may be harmless when it is uniformly distributed through stable material and dangerous when it is focused through a crack, conduit contact, poorly compacted zone, foundation lens, or discontinuous filter. The numerical results therefore support a mechanism-based interpretation in which total discharge, pore pressure, flow direction, gradient, material erodibility, filter retention, drain performance, and observational evidence are considered together. The partial drain-blockage scenario illustrates a particularly important operational problem. Drain discharge decreased from the maximum-level value even though the phreatic surface rose, downstream pore pressures increased, and the saturated zone expanded. If drain flow were interpreted without piezometric information, the lower discharge could be mistaken for improved watertightness. In reality, the model indicated restricted drainage and redistribution of seepage into the downstream shell and foundation. This confirms that monitoring thresholds should be based on relationships among variables rather than on independent alarm limits. Drain discharge should be normalized against reservoir elevation and evaluated with piezometric head, turbidity, rainfall, temperature, and operating history. A falling drain flow accompanied by stable or falling piezometric levels may reflect lower hydraulic loading, whereas falling flow with rising pore pressure may indicate clogging or loss of hydraulic connection to the measuring point. Similarly, an increase in seepage proportional to reservoir head may represent normal behaviour, while a sudden change in the slope of the seepage-head relationship can indicate a newly opened defect or progressive deterioration. Reclamation guidance likewise emphasizes the joint interpretation of seepage, instrumentation, geology, zoning, and filter performance [1-3]. The high sensitivity to the defect position also has practical significance. A high-permeability zone near the lower core-foundation contact created a shorter hydraulic pathway and connected directly with the pervious foundation, producing a more adverse response than a comparable defect at a higher elevation. This finding indicates that investigations should focus on foundation contacts, abutments, conduit interfaces, cutoff connections, and zones where differential settlement may create cracking or incomplete contact. Uniform permeability models may underestimate the risk posed by such local features because averaged parameters smooth the very concentration of flow that controls erosion. The model should therefore be progressively refined when monitoring trends, construction records, boreholes, or geophysical surveys suggest heterogeneity. Electrical resistivity tomography is particularly useful for identifying changes in saturation and anomalous zones between sparse instruments, although its interpretation is non-unique and may be influenced by temperature, material variability, electrode configuration, and scale. Recent field studies show that ERT can detect some internal defects and improve seepage-zone delineation when it is integrated with geological information, water-pressure observations, and numerical simulation rather than used as a stand-alone diagnostic method [7,8]. The combined approach is therefore most suitable: monitoring identifies behavioural change, geophysics helps localize the anomaly, targeted drilling or testing verifies material conditions, and the numerical model evaluates the hydraulic significance of the interpreted pathway. The rapid-drawdown results reveal that the governing safety condition may shift with reservoir operation. Maximum reservoir level generated the largest downstream seepage loading and the highest internal erosion potential, whereas rapid drawdown produced the most unfavourable residual pore-pressure condition in the upstream shell and core. The 1.00 m/day scenario retained substantially higher pore pressure than the 0.25 m/day case at the same final water level, demonstrating that reservoir elevation alone does not define the hydraulic state of the dam. The previous loading history and rate of change are equally important. Studies of fluctuating reservoir levels and drawdown similarly show that delayed pore-pressure dissipation, soil-water characteristic behaviour, permeability, slope geometry, and drawdown rate affect both seepage gradients and slope stability [4,5]. This has two management implications. First, an operating rule intended to reduce downstream seepage by rapidly lowering the reservoir may introduce an upstream stability problem. Second, a complete safety assessment should couple the transient seepage solution with effective-stress slope-stability analysis. The present risk index focuses on internal erosion and therefore identifies rapid drawdown as an important hydraulic condition, but it does not replace a separate stability calculation using the transient pore-pressure field. The proposed Internal Erosion Risk Index provides a useful structure for combining evidence that is otherwise reported separately. Hydraulic loading identifies the driving force; material susceptibility represents the potential for particle detachment and transport; filter and drainage deficiency evaluates whether the defensive system can arrest the process; observed anomalies reflect actual behavioural evidence; and consequences determine the urgency of action. The representative scenarios show that the filter and drainage component deserves substantial weight because an effective defensive system can tolerate relatively high seepage while a local discontinuity can convert a manageable defect into a progressive failure mechanism. Experimental research also demonstrates that concentrated leak erosion resistance depends on soil composition, dispersivity, stress conditions, and hydraulic loading, confirming that a single universal erosion criterion is unlikely to represent all fine-grained materials [6]. The index should nevertheless be treated as a transparent decision-support instrument rather than as a substitute for engineering judgement. Its thresholds are preliminary, the weights should be reviewed for each dam, and a critical observed sign such as muddy seepage, transported particles, a sinkhole, rapidly rising pore pressure, or uncontrolled leakage may justify urgent action regardless of the calculated composite value. The framework is most reliable when all component scores and their evidence remain visible to decision makers instead of being hidden behind one final number. The sensitivity analysis provides a practical way to prioritize additional investigation. Defect conductivity, drainage efficiency, and foundation anisotropy produced the greatest variation in the calculated response; consequently, uncertainty in these parameters should be reduced first. Additional piezometers across the core and near the downstream toe can distinguish drainage deterioration from changes in reservoir loading, while separate drain measurements can identify redistribution between drainage zones. Grain-size and filter compatibility tests are required where archival information is incomplete, and permeability testing or pumping tests can constrain foundation parameters. When a potential concentrated pathway is suspected, targeted ERT, temperature monitoring, tracer testing, boreholes, or inspection of conduit contacts may be more valuable than increasing the density of instruments in unaffected areas. The calibrated numerical model can then be updated through an observational approach, in which new measurements are used to test competing seepage interpretations. The results also support intervention according to the identified mechanism rather than general treatment of the entire dam. Routine monitoring is appropriate when seepage is stable, distributed, clear, and adequately filtered. Enhanced surveillance is justified when loading increases or the seepage-head relationship departs from its baseline without direct evidence of particle transport. Preventive rehabilitation is required when drains are partially blocked, pore pressures rise, filters are uncertain, or a localized anomaly persists. Urgent stabilization is warranted when concentrated leakage, muddy water, fines, sinkholes, rapidly changing instrumentation, or an unprotected exit indicates an active progression pathway. Possible measures include cleaning or enlarging drains, adding graded filters, installing relief wells, repairing conduit and abutment contacts, targeted grouting, constructing a cutoff wall or upstream blanket, restricting reservoir level, slowing drawdown, and expanding real-time monitoring. Selection should consider whether the measure reduces hydraulic loading, interrupts the pathway, retains eroded particles, restores drainage, or improves the probability of timely detection. The main limitation of the study is that the numerical values derive from a representative model rather than a calibrated site-specific dam. The conclusions therefore concern the behaviour of the proposed methodology and the relative importance of the investigated mechanisms, not the certified safety of any existing structure. The assumed geometry, permeability, drain efficiency, defect dimensions, and risk weights must be replaced by survey, laboratory, monitoring, and operational data before practical application. Two-dimensional modelling also cannot fully represent three-dimensional abutment leakage, localized defects, longitudinal zoning changes, or spatially variable foundation channels. Future work should validate the index against long-term monitoring records, incorporate probabilistic distributions and dependence among uncertain parameters, couple seepage with stress-deformation and slope stability analyses, and evaluate how proposed rehabilitation measures reduce calculated risk. Despite these limitations, the integrated procedure offers a technically coherent bridge between routine monitoring and advanced numerical analysis. Its principal value is not the production of a single risk score, but the disciplined linkage of observations, material properties, defensive-system performance, hydraulic modelling, uncertainty, and failure consequences into an auditable engineering decision.

5. Conclusion

This study developed an integrated methodology for assessing seepage behaviour and internal erosion risk in earth dams subjected to variable reservoir levels. The approach combines document review, field inspection, geotechnical testing, piezometric and seepage monitoring, saturated-unsaturated numerical modelling, filter and drainage assessment, sensitivity analysis, and a composite Internal Erosion Risk Index. The representative zoned-dam application demonstrated that total seepage discharge alone is not an adequate safety criterion. The intact model remained within routine-monitoring or enhanced-surveillance conditions because seepage was distributed and safely intercepted by continuous filters and drains, whereas partial drain blockage raised the phreatic surface and downstream pore pressure despite a reduction in measured drain flow. A localized high-

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permeability defect near the core-foundation contact produced the most critical response by concentrating flow, increasing the local hydraulic gradient, and connecting the seepage pathway with a weakened filter zone. The rapid-drawdown analysis further showed that the governing condition may change from downstream internal erosion at high reservoir level to delayed pore-pressure dissipation and potential upstream-slope instability during fast lowering. These results confirm that reservoir history, flow-path geometry, soil erodibility, filter retention, drain effectiveness, and monitoring trends must be evaluated together. The proposed risk index provides a transparent basis for classifying the dam condition as routine monitoring, enhanced surveillance, preventive rehabilitation, or urgent stabilization, but it should not override direct evidence of active erosion or professional judgement. Practical application should begin with a site-specific digital database containing dam geometry, geological zoning, material properties, reservoir hydrographs, instrument locations, piezometric response, drain discharge, turbidity, deformation, and repair history. The numerical model should then be calibrated against observed heads and flows, tested under maximum level and drawdown scenarios, and updated when new monitoring or geophysical information becomes available. Recommended interventions should target the identified failure mechanism and may include drain rehabilitation, restoration of filter continuity, relief wells, targeted grouting, cutoff or blanket construction, conduit-interface repair, operating restrictions, and additional instrumentation. Since the present calculations are illustrative, future research should apply the method to an operating earth dam, use probabilistic parameter distributions, couple transient seepage with stress-deformation and slope-stability analysis, and quantify the risk reduction achieved by alternative rehabilitation measures. Overall, the methodology supports a transition from isolated visual inspection and reactive repair toward condition-based, mechanism-oriented, and risk-informed management of earth dams.

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