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The Älvkarleby Test Embankment Dam

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ABSTRACT: The Älvkarleby test embankment dam was constructed as a large-scale physical model to investigate damage detection, mechanical behaviour and internal erosion of embankment dams under controlled conditions. Designed in accordance with Swedish dam safety guidelines, the 4 m-high dam incorporated intentional defects and was instrumented with a comprehensive suite of geotechnical and geophysical monitoring systems. The project aimed to evaluate the performance of these monitoring techniques, assess the dam's response to initial impoundment and cyclic reservoir level fluctuations, and examine the effectiveness of remedial grouting. The results demonstrated that traditional sensors effectively captured pore-pressure and deformation trends, while advanced monitoring methods, such as 3D electrical resistivity tomography and distributed acoustic sensing, provided valuable insights into subsurface anomalies. The dismantling of the dam confirmed several of the monitoring-based observations, including the development of a preferential seepage path near the base of the core. The study highlighted the importance of integrating multiple monitoring approaches and accounting for scale effects when interpreting experimental results. While quantitative extrapolation to full-scale embankment dams required caution, the qualitative findings — particularly those related to internal erosion mechanisms and the influence of operational variability — were directly transferable to real-world applications. Overall, the project underscored the potential of combining instrumentation, modelling, and physical validation to enhance dam safety and to inform the development of future monitoring strategies.

1 INTRODUCTION

Hydropower embankment dams represent ageing infrastructure that must operate with near-perfect reliability. A significant threat to their integrity has been internal erosion of the impervious core, a process that often remained undetected until symptoms such as increased leakage or sinkhole formation became apparent (Norooz et al., 2024). To enhance early detection and facilitate preventive maintenance, Vattenfall AB, in collaboration with Swedish research partners, constructed an experimental embankment dam at the Älvkarleby R&D laboratory in 2019. This 4-metre-high structure was designed as a scaled-down, yet geometrically accurate model of a typical Swedish embankment dam, in accordance with national dam safety guidelines (Toromanovic et al., 2022). The project had two primary objectives:

1. Observe the dam's mechanical behaviour during operation.
2. Evaluate advanced monitoring techniques for detecting internal damage within a controlled environment.

By integrating multiple disciplines, including geotechnical, geophysical, and hydraulic engineering, the test dam provided valuable insights into dam performance and safety measures that could inform the management of full-scale dams. This paper presents a summary of the project, highlights key findings, and discusses how the reduced scale may have influenced these findings and their applicability to large-scale dams.

2 MATERIALS & METHODS

The Älvkarleby test dam was constructed within a watertight concrete containment box measuring 20 m × 16 m at the base, with a depth of 4 m (Toromanovic et al., 2022). The concrete containment box enabled a reservoir to form upstream of the dam and precise control of reservoir water levels and seepage collection, see Figure 1.

Figure 1. Overview of the concrete containment box and test embankment dam prior to the installation of an uninsulated tent.

The dam was a zoned embankment dam with a central glacial till core (low-permeability moraine) surrounded by filter zones (fine sand/gravel filter and coarser gravel filter), and outer rockfill shoulders to provide stability. All materials and layer thicknesses were selected in accordance with Swedish guidelines (RIDAS) to satisfy filtering and stability criteria, scaled appropriately to the reduced dimensions of the structure (Toromanovic et al., 2022; Norooz et al., 2024). The dam measured approximately 20 m in length and 15 m in width, and it was constructed in 0.2 m thick layers using standard earthwork techniques, see Figure 2. To protect the embankment dam from precipitation during operation, an uninsulated tent was erected over the concrete containment box.

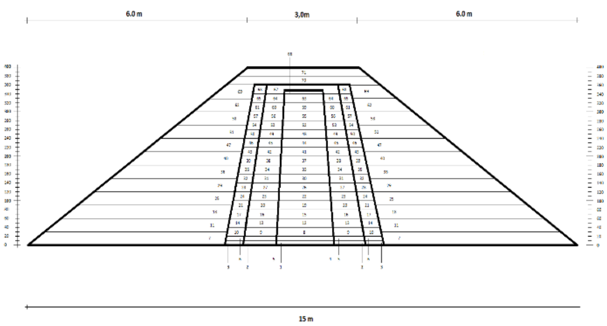

Figure 2. Cross section of the embankment dam.

A distinctive feature of the test dam was the deliberate incorporation of known defects within its core during construction, simulating internal flaws or damage that might occur in ageing dams. These artificial defects included a 0.4 m wooden block to represent a void or “cavity”; gravel-filled zones simulating high-permeability layers (both horizontal and vertical) and a 0.5 m concrete block acting as a large rogue inclusion (Norooz et al., 2024). Additionally, a small section of missing filter material was introduced into the upstream filter. Locations of the defects in the core soil of the dam are shown in Figure 3. The locations and characteristics of these six defects were kept blind to the monitoring researchers, creating a realistic challenge to assess whether various instruments could detect them. Importantly, none of the defects individually compromised the dam’s overall integrity, i.e., the dam could be safely filled, but they served as intentional weak points and inhomogeneities for the monitoring systems to identify and localize.

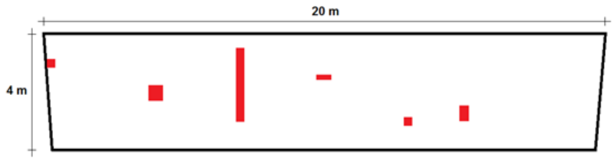

Figure 3. Location of incorporated defects viewed from the upstream side toward downstream side. Description of defects from left to right: horizontal high permeable zone; concrete cube; vertical high permeable zone; horizontal high permeable zone; wooden cube; separated filter defect in upstream fine filter.

2.1 Instrumentation & Monitoring

The dam was extensively instrumented with both traditional geotechnical sensors and geophysical sensor technologies.

Twelve vibrating-wire pore pressure transducers were installed at multiple levels within the core and filter zones to monitor internal water pressures (Toromanovic et al., 2025). Three in-place inclinometer chains, i.e., Shape-Accel-Arrays (SAA), were vertically embedded in one section of the dam in the upstream slope, central core, and downstream slope to continuously measure deformations (Toromanovic et al., 2022). Furthermore, a pre-tensed strain cable, along with a temperature cable, was installed 0.2 m from the bottom in a continuous loop upstream-to-downstream direction to detect movements at the base of the dam. The pre-tensed strain cable traversed the core at four locations, one meter apart.

On both the upstream and downstream side of the core, two loops of fibre-optic cables were laid out in the fine filter during construction. Measurements of temperature were performed, enabling the detection of seepage zones inside the dam. In addition, a distributed acoustic sensing (DAS) system, using the same fibre optic cables, was deployed to capture vibrations or acoustic signals associated with seepage flows or soil movements (Johansson et al., 2022).

Custom made cables for three-dimensional electrical resistivity tomography (ERT) were installed to enable three-dimensional resistivity imaging of the dam's interior (Norooz et al., 2024). The cables contained electrode plates and were installed inside the dam (including lines across the crest, mid-core, base, and abutments). This ERT system collected thousands of data points daily, effectively monitoring changes in the dam's moisture and material distribution over time.

Finally, hydrophone cables were installed at the bottom and top of the core. Seismic surveys could thus be conducted to detect stiffness anomalies that might indicate internal erosion or loose zones. All three types of geophysical cables at the crest of the core can be seen in Figure 4.

All seepage that percolated the dam was collected at the downstream toe via a controlled drainage system (8 separate Thomson weirs) and monitored for leakage rate and turbidity. Thanks to the tent, no precipitation disturbed the measurements of seepage. Turbidity in the seepage discharge, measured once a week, signalled whether soil particles were being transported, i.e., a direct indication of internal erosion. This comprehensive instrumentation ensured that any change in the dam could be observed by one or more systems.

Figure 4. Fibre optic cable (yellow), ERT cables (green/silver) and hydrophone cables (red) at the crest of the core soil before being covered with fine filter and shell fill.

2.2 Operational Procedure

In March 2020, the dam underwent its initial impoundment. Water from the Dala River was pumped into the concrete containment box to fill the reservoir against the upstream face of the dam. The filling was carried out incrementally: beginning in mid-March 2020, the water level was raised in stages, with brief pauses for monitoring (Toromanovic et al., 2022). After approximately three weeks, the reservoir reached a depth of ~2 m and was temporarily lowered to upgrade the seepage monitoring capacity for higher levels. By June 2020, the reservoir attained its maximum level of ~3.5 m, just below the dam crest. This represented the scaled equivalent of a full reservoir for the test dam. Thereafter, the water level was maintained near 3.3 m for an extended period, allowing the dam to operate under steady-state full-reservoir conditions.

Throughout this initial filling and steady operation, all instruments continuously logged data. Once the dam's response had stabilised, the project progressed into a phase of deliberate stress testing. In early 2022, the reservoir was cyclically lowered and raised on five occasions, from near-empty back to ~3.3 m (Toromanovic et al., 2025). These five drawdown–refill cycles were conducted to simulate fluctuations in a hydropower dam's water level, such as those caused by varying power demand or flood control, and to investigate how repeated hydraulic loading might influence the embankment's internal stresses and the development of erosion paths. Later in the project, another realistic intervention was trialled: the dam's core was subjected to remediation grouting. Holes were drilled from the crest into the core, and a pressurised novel grout material, (Lagerlund, 2024), was injected, while instruments monitored for any induced fractures or changes (Lagerlund et al., 2023).

After approximately four years of service, the experiment culminated in a controlled dismantling of the dam in 2024. The dam was gradually excavated layer by layer to allow visual inspection of its interior. This "autopsy" enabled researchers to locate the artificial defects and observe any actual internal erosion or material changes that had occurred during operation. Every observation made during dismantling was meticulously documented (Lagerlund and Riaz., 2026). This final step was critical: by comparing the physical findings with the instrument data, the monitoring teams were able to validate which monitoring techniques successfully detected specific forms of internal damage, and which had failed to identify or had misinterpreted changes.

3 RESULTS

3.1 Initial Structural Performance

During the first impoundment, the test dam remained stable and behaved largely as expected for a well-constructed embankment dam. Pore pressures within the core rose steadily with the reservoir level, albeit slightly more slowly than predicted by preliminary finite-element models. For instance, the lowest piezometers (located near the core base) lagged behind the reservoir rise, indicating that full saturation of the core required additional time (Toromanovic et al., 2022). After approximately a year of operation, the pore pressures within the core established a typical steady-state distribution, high near the upstream face and decreasing towards the downstream filter. However, this was not long-lasting, as the pressures were re-distributed in the core. The observations suggested a redistribution of permeability: the lowest section of the core likely experienced internal erosion or compaction, increasing its permeability (thus facilitating pressure dissipation), while a zone slightly above it became less permeable (Toromanovic, 2024).

Deformation measurements revealed that the dam experienced moderate settlement and lateral strain during filling. Downstream movement of the core and shoulder was on the order of a few millimetres, increasing from the upstream to the downstream side, consistent with the water load exerting outward pressure on the dam (Toromanovic et al., 2022). These horizontal deformations corresponded well with zones of elevated strain detected by the base fibre-optic cables, indicating different material zones. Higher strains at the downstream side of the dam were observed in some sections, which can be a sign of activation of shear stresses at the base of the dam due to the sloping concrete bottom towards the downstream side. The impoundment was responsible for most of the additional strain developments. The strains developed over time after the reservoir was at its maximum level. This indicated transient processes were taking place, and not the theoretically assumed steady state of a quick development of the saturated zones under the seepage line (Toromanovic et al., 2025b). The dam's seepage rate at full reservoir level remained low, and the downstream water was clear (with no significant turbidity), confirming that the initial impoundment did not induce detectable internal erosion.

3.2 Dam Response to Reservoir Fluctuations

The series of five reservoir drawdown and refill cycles conducted in 2022 revealed more subtle effects. Pore pressure monitoring proved particularly insightful during this phase. During each drawdown, pore pressures in the upstream portion of the core decreased as expected, then recovered when the water level was restored. Initially, these pressure changes were largely elastic, with pressures returning to their previous values after each cycle. However, after successive cycles, a small but notable trend emerged: the bottom-most core piezometer (P3) on the downstream side did not fully recover to its prior pressure, instead registering a lower value than before (Toromanovic et al., 2025). By the final (fifth) cycle, P3's readings had permanently decreased and were approximately equal to the pressures measured higher up in the core, indicating that the lowest part of the core was now more effectively relieved by seepage flow. In essence, water had found an easier path through the core.

In contrast, piezometers located in the upper core exhibited a slight increase in residual pressure after multiple cycles. (Toromanovic et al., 2025). Notably, following the cycles, seepage measurements indicated a modest increase in leakage rate and minor turbidity spikes, consistent with the development of a fine leak path. These results provided evidence that repeated reservoir level fluctuations, as may occur in modern flexible hydropower operations, could induce or accelerate internal erosion processes, even in a properly designed dam. In the test dam, the effect was modest but measurable: a continuous low-pressure void or high-permeability channel had effectively formed near the core base by the end of the cycling. This finding underscored the importance of monitoring long-term changes in dam core conditions under fluctuating hydraulic loads.

3.3 Integrated Monitoring and Defect Detection

The suite of geophysical monitoring techniques yielded a comprehensive assessment of the dam's internal behaviour. The vibrating-wire piezometers identified the internal erosion development described above, thereby demonstrating the value of high-resolution conventional instrumentation. Meanwhile, the ERT surveys successfully captured some of the known defects and anomalies within the dam, albeit with varying degrees of success, see Figure 5.

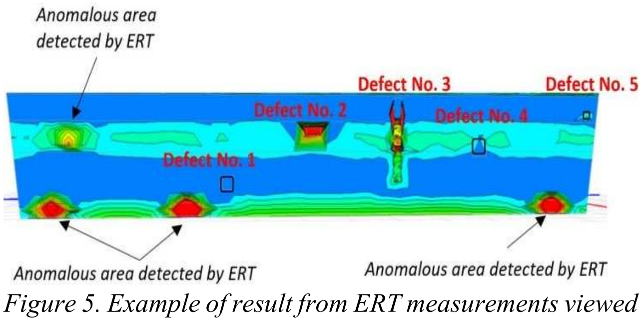

Figure 5. Example of result from ERT measurements viewed from the downstream side toward upstream side (opposite as shown in Figure 3) Although these signals were still under analysis.

The 3D time-lapse resistivity inversions revealed a distinct layered resistivity structure corresponding to the dam zoning and identified several unexpected anomalous zones within the core (Norooz et al., 2024). For example, regions of slightly elevated resistivity were detected in the core which, upon subsequent investigation, did not correspond to the intentionally placed defects but were instead attributed to unintentional material heterogeneities, such as small pockets of drier soil or soil of differing density.

Importantly, ERT monitoring successfully identified two of the five deliberately embedded core defects, namely the horizontal high-permeability layer in the central core (Defect No.2 in Figure 5) and the vertical gravel column (Defect No.4 in Figure 5). These features manifested as localised resistivity anomalies that were distinct from the natural background, although their positions were slightly displaced in the inversion images (Norooz et al., 2024). A third defect, the concrete block (Defect No.3 in Figure 5) intended to simulate a boulder, was only weakly indicated in the resistivity data as a moderately resistive zone and was not clearly resolved. The remaining defects, including the second horizontal layer near the abutment (Defect No.5 in Figure 5) and the wooden cube (Defect No.1 in Figure 5), were effectively undetected by ERT, probably because they did not generate a sufficiently strong resistivity contrast under the prevailing seepage conditions.

The seismic methods employed provided additional insights. Preliminary seismic velocity tomography delineated stiffness contrasts within the dam that corresponded to the large concrete block and possibly the looser gravel zone, thereby complementing the ERT results.

Fibre-optic strain measurements did not show any pronounced strain concentrations that would have indicated localised settlement. However, distributed acoustic sensing (DAS) detected notable signals during periods of rapid drawdown and throughout the grouting operations. Specifically high-frequency vibration patterns consistent with transient water flow surges and cracking phenomena were detected. Although these signals were still under analysis at the time of submission, they suggested that DAS had the potential to provide sensitive detection of processes such as soil crack initiation or increased leakage (Johansson et al., 2022).

In summary, the multi-method monitoring approach proved effective. Each technique offered complementary strengths: geotechnical instruments supplied quantitative measurements of pore pressures and deformations essential for safety evaluation, while geophysical methods enabled volumetric interrogation of the dam to detect concealed anomalies. The integration of multiple monitoring methods therefore provided a cross-validated understanding of the dam's internal condition that could not have been achieved as comprehensively by any single technique alone.

3.4 Dismantling Observations

The sequential dismantling of the dam confirmed many of the predictions derived from the monitoring programme and also revealed some unexpected findings. All artificial defects were recovered at their intended locations, and the surrounding soil exhibited changes consistent with the recorded measurements. Notably, in the downstream half of the core near the base (approximately at the location of piezometer P3), the soil showed clear evidence of internal erosion. A subtle flow channel and deposits of transported fine material were observed, indicating enlargement of the originally placed loose zone between the core and the filter. This physical evidence corroborated the abnormally low pore-pressure readings and the slight increase in leakage turbidity measured after reservoir cycling, effectively demonstrating that a small internal pipe had begun to form along the core–filter interface at the foundation level, see Figure 6.

Internal erosion of the core soil was identified in several locations within the lower half of the dam. In particular, initiated internal erosion was found in between the core soil layers. The primary cause was most likely that the delivered core material was finer than anticipated in the design specifications. As a result, the fine filter material, although supplied according to design, was effectively too coarse to satisfy the required filter criterion for the actual core gradation. Additionally, the delivered core soil had an excessively high moisture content. Due to the onset of winter and project time constraints, the material had to be placed without adequate drying. This high moisture content prevented proper compaction, reducing the achieved density and increasing susceptibility to internal erosion. Despite these issues, no uncontrolled internal erosion occurred in the sense of a progressing pipe or breach. The eroded fines were successfully retained within the filter zones, and the overall integrity of the dam remained uncompromised.

Another significant observation was that the grouting operation in the core left visible traces of grout within fractures generated during injection when grouting pressures were too high (intentionally chosen too high). The core material around the grout holes exhibited newly formed, thin cracks filled with grout, indicating that high-pressure grouting was capable of inducing hydraulic fracturing in a small dam. Fractures always occurred in between layers of core soil and in an upstream orientation. This finding suggested the need for caution when applying grout rehabilitation measures, while also demonstrating that the grout treatment effectively sealed some of the deliberately constructed defects (Lagerlund et al., 2023).

The embedded instrumentation largely remained intact, and recorded measurements corresponded closely with the observed soil conditions. For example, inclinometers installed near the downstream slope registered a small lateral displacement consistent with the offset that was visually detected during dismantling. Internal degradation, and areas highlighted by monitoring data, such as the eroded zone at the core–filter interface, were confirmed through direct inspection.

These findings were compiled into a comprehensive report (Lagerlund and Riaz, 2026), which provided a detailed reference demonstrating how internal dam processes were reflected both in instrument responses and in the physical condition of the embankment material.

Figure 6. Eroded core soil removed, leaving the intact core soil in place during dismantling. Damage ~120 cm deep with an estimated volume of 300 litres.

4 DISCUSSION

4.1 Mechanical Behaviour and Internal Erosion at Reduced Scale

The height of the Älvkarleby test dam, at 4 m, placed it in the category of large-scale physical models; however, it remained substantially smaller than typical embankment dams, which often exceed 15 m in height. This difference in scale introduced notable scale effects, particularly with respect to vertical effective stresses and hydraulic gradients. For example, the vertical stress at the base of the test dam was approximately 80 kPa, compared with around 800 kPa in a 40 m-high embannkment dam. This disparity directly influences the mechanical behaviour of the soil, including its susceptibility to internal erosion and crack initiation (Halvorsen et al., 2024; Mohamed et al., 2016).

The internal erosion observed near the downstream base of the core, inferred from reduced pore-pressure measurements and subsequently confirmed during dismantling, may have initiated more readily as a result of the lower confining stresses present in the model dam. In full-scale embankment dams, higher overburden pressures would be expected to delay or inhibit the onset of such erosion processes. Conversely, once erosion is initiated in larger dams, it could be expected to progress more rapidly owing to higher hydraulic heads and greater seepage volumes (Mohamed et al., 2016). Consequently, although the test dam provides valuable qualitative insight into erosion mechanisms, caution is required when extrapolating quantitative thresholds or critical conditions directly to real embankment dams.

The exclusion of particles >20 mm from the moraine in the scaled test likely increased the core's susceptibility to internal erosion compared to full-scale dams. Coarse particles in natural tills enhance internal stability by limiting fine particle migration (Sherard, 1979). Their absence may have facilitated erosion initiation and progression, especially where filter compatibility was compromised (Sherard and Dunnigan, 1989). Filters too coarse relative to the base soil can fail to arrest erosion once initiated (Foster and Fell, 2001). Thus, the observed erosion in the test dam may be conservative, highlighting the importance of gradation fidelity in scaled models.

4.2 Monitoring Technologies and Scalability

The test dam served as a proving ground for a suite of monitoring technologies, including vibrating-wire piezometers, SAA, fibre-optic strain and temperature sensing, DAS, and 3D ERT. The successful detection of two out of five embedded defects using ERT, together with the identification of anomalous zones that did not correspond to known defects, demonstrated the method's sensitivity and potential (Norooz et al., 2024; Norooz et al., 2025). However, the scalability of these technologies to full-scale dams presented several challenges. For instance, the resolution of ERT decreased with increasing depth and electrode spacing, and 3D inversion became computationally demanding for larger domains (Bièvre et al., 2018). Similarly, DAS systems were susceptible to signal attenuation over longer sensing distances, which could limit their effectiveness in large embankment dams.

Seismic results were most likely affected by the concrete containment box into which the experiment took place. This most likely caused echoes when peforming the seismic measurements, making it difficult to intepret the results.

Nevertheless, the results obtained from the test dam validated the integrated use of geophysical and geotechnical monitoring techniques, indicating that hybrid monitoring approaches could enhance the early detection of internal erosion processes in full-scale dams (Norooz et al., 2024b; Cho et al., 2014).

4.3 Hydraulic Boundary Conditions and Time-Scale Effects

The concrete containment box ensured that all seepage was confined to the embankment dam body, thereby simplifying the interpretation of internal erosion processes. In contrast, full-scale dams are frequently founded on pervious substrates, which introduce more complex seepage pathways that can obscure indicators of internal erosion (Fargier et al., 2014). Furthermore, the time scales of processes observed in the test dam, such as the development of preferential flow paths, may have been accelerated relative to those in prototype dams owing to smaller pore volumes and the absence of maintenance or remedial interventions.

Despite these differences, the qualitative findings were considered transferable. For example, the observed correlation between anomalous pore-pressure trends and internal erosion represented a robust indicator applicable across different scales. The performance of the test dam under cyclic reservoir loading conditions also reflected concerns encountered in real dams operated under flexible energy regimes, where frequent water-level fluctuations can create new seepage paths and increase the susceptibility to internal erosion (Toromanovic et al., 2025).

5 CONCLUSIONS

The Älvkarleby test embankment dam project demonstrated the value of a multidisciplinary approach to understanding embankment dam behaviour and monitoring. Constructed as a scaled physical model of a typical Swedish embankment dam, the test dam enabled controlled experimentation involving embedded defects, advanced instrumentation, and varied operational scenarios, including cyclic reservoir loading and remedial grouting.

The project confirmed that traditional geotechnical instrumentation, such as pore-pressure transducers and deformation sensors, remained essential for capturing the mechanical response of the dam. At the same time, the integration of geophysical methods, particularly 3D electrical resistivity tomography and distributed acoustic sensing, provided complementary information on internal conditions and potential anomalies. The dismantling phase validated many of the monitoring outcomes, thereby increasing confidence in the interpretability and reliability of the applied techniques.

Although scale effects required careful consideration when extrapolating the findings to full-scale dams, the qualitative behaviours observed, including the development of preferential seepage paths and the influence of reservoir level fluctuations on internal erosion processes, were directly relevant to practical dam safety assessments. The project also highlighted the importance of accounting for three-dimensional effects in both monitoring strategies and modelling efforts, particularly when interpreting data from embankments with complex internal zonation.

Overall, the Älvkarleby test dam served as a benchmark for future research and operational practice. It provided a validated framework for combining instrumentation, modelling, and physical inspection to improve the safety and resilience of embankment dams in the context of ageing infrastructure and increasingly dynamic operational conditions.

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