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OBSERVATIONS FROM CYCLES OF VARYING RESERVOIR LEVELS ON AN EXPERIMENTAL EMBANKMENT DAM

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ABSTRACT

In 2019, Vattenfall AB together with several researchers, built an experimental embankment dam in Älvkarleby, Sweden. The dam was a four metres high small-scale conventional rockfill dam. The design and construction methods followed the Swedish dam safety guidelines for conventional dams. The dam was zoned, with a core made of glacial till, surrounded by fine and coarse filter zones and shoulder material. The dam was built and finalized in November 2019. Pore pressure, seepage, deformations and strains have been monitored in the dam. The impoundment of the dam was conducted in the first half of 2020, thereafter the water level in the reservoir was kept constant until early 2022. Then five cycles of emptying and filling up of the reservoir were conducted to evaluate the effects on the cyclic conditions of the embankment dam. In this contribution, the effects of varying reservoir levels on the dam body are assessed, based on the results from the monitoring of the pore pressures. Varying reservoir levels in hydropower dams, in a larger extent is usual today due to the new more flexible energy market, and are thus relevant for existing dams in the green transition.

Keywords: embankment dam, pore pressure, reservoir fluctuations.

INTRODUCTION

An experimental embankment dam was built as a collaboration between Vattenfall AB and research groups from Luleå University of Technology, Uppsala University, Lund University of Technology and HydroResearch AB. One purpose was to study the mechanical behaviour of the embankment dam during its first impoundment as well as throughout the continued operation. Another purpose was to test how well different geophysical methods, such as e.g. resistivity and tomography, in a blind test could detect various purposefully built-in defects embedded in the dam core, see Viklander et al. (2023). The dam built was a conventional rockfill dam, constructed similar to many existing embankment dams in Sweden. It is a smaller dam in height compared to most of the existing structures, but can be considered a large-scale experimental dam. The dam was designed and constructed after Swedish guidelines, RIDAS (2011). Geotechnical monitoring was performed using pore pressure transducers in the core, inclinometers in upstream, middle and downstream shoulder, and strain measurements near the interface at the bottom of the foundation. Measurements were done before and during reservoir filling as well as during the operational phase. Vattenfall AB was funding the construction of the experimental dam built at the research and development laboratory in Älvkarleby, Sweden. Vattenfall R&D was responsible for the operation and maintenance of the dam during the project. In previous publications, e.g. Toromanovic et al. (2022), Toromanovic (2024) and Toromanovic et al. (2025), data from the period from when the construction of the dam was finalized, in November 2019 up until August 2021, was reported. This study focuses on the effects on the pore pressures in the dam, when exposed to cyclic fluctuations of the reservoir levels. Prior to mid-September 2021, the operation level was constant most of the time.

THE EXPERIMENTAL EMBANKMENT DAM

The experimental dam was built inside a surrounding support structure made of reinforced concrete. The structure measured 20 meters by 16 meters, with its foundation located 4 meters below ground level. During the first winter season, the dam was protected from freezing by heating. The bottom slab is one degree inclined towards the downstream side to enable measurement of seepage downstream the dam toe. The abutments of the support structure were inclined outwards, to achieve a sufficient connection to the wall when compacting the core material.

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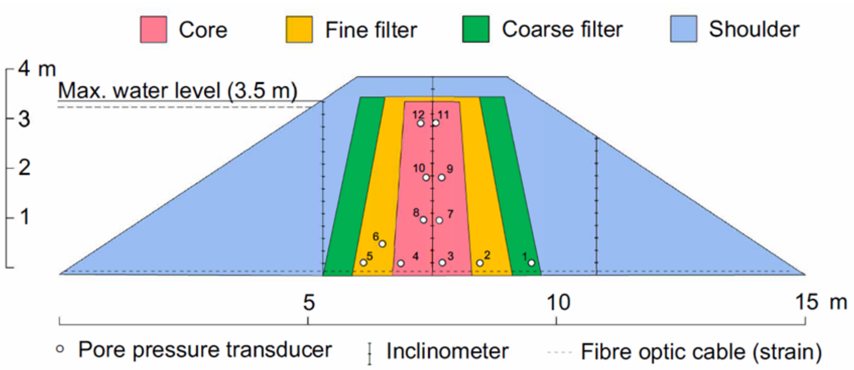

Figure 1 *Cross-section of the four metres high experimental embankment dam*

In order to have a controlled environment, a tent was raised after finalizing the construction of the embankment dam, to protect it from precipitation and large temperature fluctuations. During the subsequent winter season, air temperatures below zero degree were allowed in the tent. The river Dalälven was supplying the dam with reservoir water. Seepage water was recycled after sedimentation.

The dam was built with a conventional zoned construction, featuring a central core made of glacial till, which was surrounded by fine and coarse filter layers, as shown in Figure 1. Rockfill material was placed as shoulder fill outside the filter zones. The embankment dam was designed according to the Swedish dam safety guidelines, RIDAS (Swedenergy, 2011). The finished dam was 4 meters high, 20 meters long, and 15 meters wide. The dam construction took four weeks to complete. The dam was built in layers, each 20 centimetres thick in the core. A detailed description of the construction process is provided in Toromanovic et al. (2020). An overview of the soil characteristics values for the different dam materials are shown in Table 1. These values were obtained from field and laboratory tests. The values for the coarsest materials were taken tabulated values in RIDAS. More detailed information about the materials and the laboratory methods used can be found in Bernstone et al. (2021) and Toromanovic (2024). The water level in the experimental dam was continuously logged on the upstream side. In Figures 2A-C, the measured water levels are shown along with the pore pressure readings. The embankment dam was first impounded in March 2019, and the water level was kept mostly constant until mid-September 2021. Between mid-September 2021 and March 2022, five controlled water level fluctuations were carried out. The rates of lowering and raising the reservoir level varied, as did the time intervals between each step. The data presented in this paper also includes periods just before and after the fluctuations.

Table 1 *Characteristic values of materials in the embankment dam. Note: 1Bulk unit weight is presented first, with saturated unit weight in parenthesis. 1,2Values with asterisk are from RIDAS (Swedenergy, 2011).*

Parameter	Core	Fine filter	Coarse filter	Shoulder
Type of soil	Fine grained till	Sand gravel	Gravel	Rockfill
Unit weight1 [kN/m^3]	22.8 (23.5)	20.3 (21.0)	17 (19)	18* (20*)
Friction angle2 [°]	44	36*	40*	41*
Hydraulic conductivity [m/s]	5.3E-8	5.6E-5	1.8E-1	2.8E-1

Pore pressures were measured by vibrating wire piezometers in the core and in the filters of the embankment dam, positioned as shown in Figure 1. The piezometers were installed during construction and placed directly on a layer of compacted soil. The pore pressure transducers were of the type Geosense VWP-3400, with a measuring range from -70 kPa to 345 kPa. The vibrating wire within the sensor is in a closed system, which will be influenced by pressure changes outside the transducer. All pore pressure readings presented in this paper have been corrected for the air pressure and for temperature.

RESULTS FROM PORE PRESSURE MONITORING

The results of the pore pressure measurements are presented in Figures 2A-C. The numbers P1-P12 of the transducers, used in the graphs, correspond to the positions of the transducers shown in Figure 1. All readings were reset to zero at the start of the impoundment to avoid influences of the period before impoundment.

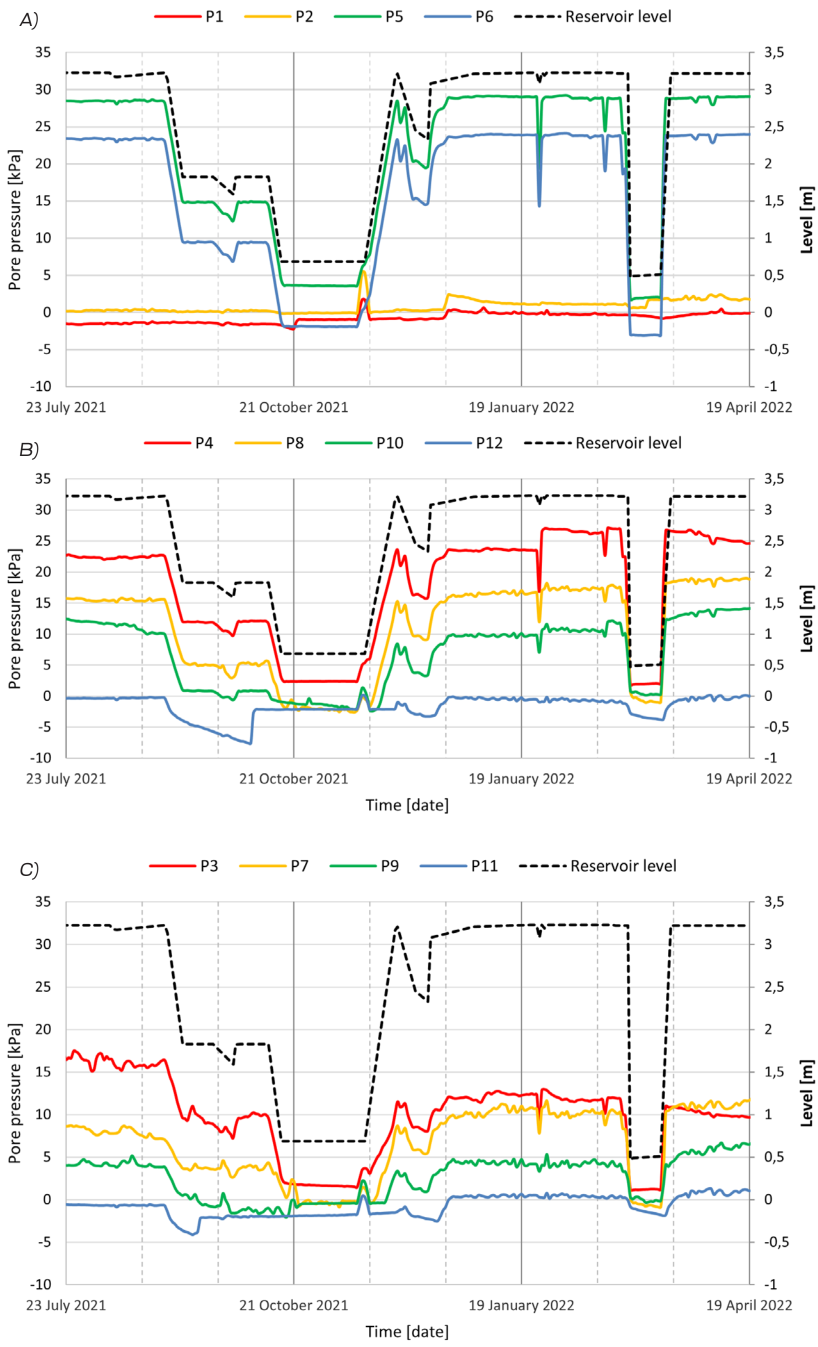

Figure 2 *Pore pressure measurements in A) the filters of the dam, P1-P2 and P5-P6, B) the upstream part of the core, P4, P8, P10 and P12, and C) the downstream part of the core, P3, P7, P9 and P11*

Figure 2A is showing the pore pressure in the coarser parts of the embankment dam; P1 is located in the coarse filter downstream, P2 in the fine filter downstream as well as P5 and P6 in the fine filter upstream respectively. Following can be observed

- The transducers P5 and P6, are reacting quickly to the changes in the reservoir level, as expected as they are located in a permeable material on the upstream side.
- The pressure in the downstream filters have minor response from the fluctuations.

In Figure 2B, the pore pressures in the upstream part of the core are shown for transducers P4, P8, P10 and P12. Due to their installation levels, the highest pressure is expected in P4, followed by P8, P10 and P12. The following can be seen in Figure 2B:

- During the two first fluctuations there are similar rates for changes in all transducers. Some suction is developing in the topmost transducer. All pressures recover to values close to the initial ones after unloading.
- After the third fluctuation, there is an elevated pressure in the bottommost transducer P4.
- After the final fluctuation, some re-distribution of pressure is observed in P4, P8 and P10.

In Figure 2C, the results of the pore pressures in the downstream part of the core are shown corresponding to transducers P3, P7, P9 and P11, and the following can be observed:

- There are less effects observed of the fluctuations at the downstream side of the core after the first fluctuation, as can be expected as the pressure is dropping towards the fine filter.
- After the second fluctuation, all pressures recover to values close to the initial ones, except the bottommost transducer P3. The pressure is significantly lower. As discussed in Toromanovic (2024), low pressure at the bottom of the core might indicate that the water has found an easier path and that internal erosion might be on-going.
- After the final fluctuation, the pressure in the bottommost transducer is still too low.

CONCLUDING REMARKS

During the impoundment and operation, the behaviour of the experimental embankment dam has been monitored in terms of pore pressure, deformation and strain. In this paper, the effects on the pore pressure from fluctuations in the reservoir level are presented.

The results indicate that pore pressures within the filter zones are marginally influenced by the fluctuations. The upstream part of the core shows signs of incomplete recovery of pore pressure at the bottom of the core, the levels are somewhat elevated. More distinct changes were observed in the downstream part of the core, where the pore pressure at the bottom remains clearly lower than expected. The pressure levels do not return to their pre-fluctuation values and instead align closely with those measured approximately one metre higher in the core.

When exploring more flexible loading scenarios for embankment dams, the effects of the cycles on the dam body need to be investigated. The experimental dam has experienced changes in the pore pressures in the bottom of the core after the five reservoir fluctuations. The fluctuations have lead to re-distribution of pressure. In future research, the effects of fluctuations will be assessed from different angles, e.g. experimentally, with focus on internal erosion, as well as predictions by numerical modelling.

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REFERENCES

Bernstone, C., Lagerlund, J., Toromanovic, J. & Juhlin, C. (2021). Deformationer och portryck i en experimentell fyllningsdamm (Deformation and pore pressure in an experimental embankment dam). Report 2021:772, Energiforsk. (In Swedish)

Swedenergy. (2011). RIDAS 2011 - Swedenergy's dam safety guidelines. Energiföretagen, Stockholm.

Toromanovic, J, Lagerlund, J, Viklander, P and Laue, J. (2020). Geotechnical instrumentation of an experimental embankment dam. Proceedings of the 4th European Conference on Physical Modelling in Geotechnics.

Toromanovic, J. (2024). Monitoring and Modelling of Embankment Dams, PhD Thesis, Luleå University of Technology. Available at: LINK, accessed at: 26/03/2025.

Viklander, P., Lagerlund, J., Riaz, S., Nordström, E., (2023). Non-destructive test methods for detecting faults in an experimental embankment dam. Hydropower and Dams 30(3): 74-71.